Renewable and Sustainable Energy Reviews 30 (2014) 85–104

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Progress in silica gel–water adsorption refrigeration technology

Dechang Wang [a,b,*], Jipeng Zhang [a], Xiaoliang Tian [a], Dawei Liu [a], K. Sumathy [b]

[a] College of Electromechanical Engineering, Qingdao University, 308 Ningxia Road, Qingdao 266071, China
[b] Department of Mechanical Engineering, North Dakota State University, Fargo, ND 58108, USA

ARTICLE INFO

Article history:
Received 9 January 2013
Received in revised form
29 August 2013
Accepted 11 September 2013
Available online 16 October 2013

Keywords:
Silica gel–water
Adsorption refrigeration
Working pair
Applications
Development

ABSTRACT

The silica gel–water adsorption refrigeration has attracted much attention especially in the last two decades, due to its environmentally friendly refrigeration that can be powered by low grade heat source. In this paper, we reviewed the research about silica gel–water adsorption technology, cooling systems as well as heat pumps. The technological developments of silica gel–water adsorption refrigeration, including working pairs, heat and mass transfer, cycle and system design, simulation work, prototypes and applications, were discussed. The advantages of silica gel–water adsorption refrigeration technology as well as its disadvantages were elucidated. Finally, the prospect of this refrigeration method was analyzed. The weak heat and mass transfer performance of the adsorbent material was the main bottleneck of the silica gel–water adsorption refrigeration technology and resulting in large size, low performance and high cost.

Contents

1. Introduction

With the rapid development of global economy, the world primary energy consumption is surprisingly increasing year by

* Corresponding author at: College of Electromechanical Engineering, Qingdao University, 308 Ningxia Road, Qingdao 266071, China. Tel./fax: +86 532 8595 0512.
E-mail addresses: wdechang@163.com, dcwang@qdu.edu.cn (D. Wang).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.09.023

year. In 1985, the annual world primary energy consumption was about 7400 million tons oil equivalent, but this number increased to 12,200 t in 2011 [1]. In 2010 [2], about 41% of the total primary energy was consumed by residential and commercial buildings. According to estimation data [3], about 73% of the total electricity is consumed by buildings in the United States and Heating, Ventilation, and Air Conditioning (HVAC) systems generate 33% of the total building energy consumption. This quotient would be massively increasing with improvement of living level especially in developing countries.

With the energy crisis and increasing of energy consumption by HVAC, some energy utilization problems conflict to the low grade energy waste. On the one hand, a large number of electric energy is consumed by cooling equipments of vapor compression refrigeration systems (such as air conditioners and refrigerators) in HVAC, and on the other hand a surprisingly large amount of waste heat from industrials and fuel engines is discharged into natural surroundings. According to statistical estimation, in summer the indoor air conditionings in cities of China had consumed about 25–70 billion kWh electric energy in 2005. Moreover, in Japan, a tremendous amount of heat energy below 100 °C was discharged into the atmosphere as waste heat, accounting for approximately 80% of the heat loss [4]. Vast waste heat discharge has caused a serious thermal pollution to environments. Simultaneously, large electricity consumption has taken a heavy burden to power plants. More and more power plants are needed to be built. Therefore, besides the improvement of the traditional compression refrigeration, development of refrigeration technology driven by waste heat may be a better solution to this problem. Adsorption refrigeration is one kind of refrigeration technology that can satisfyingly use waste heat.

Adsorption refrigeration can be seemed as environmentally friendly cooling technology without ozone depletion potential and global warming potential. It is one of the interesting and potential candidates to substitute conventional refrigeration based on vapor compression. Researchers around the world are currently attempting to develop adsorption refrigeration for its possible implementation in commercial and industrial applications [5–8]. Furthermore, the energy crisis prompts an opportunity of adsorption refrigeration to be as one alternative replacement of conventional refrigeration, especially for silica gel–water adsorption.

Silica gel–water adsorption refrigeration technology is booming in recent decades because of its suitability for low grade heat source. Compared to absorption refrigeration, another refrigeration method that can be powered by heat, silica gel–water adsorption refrigeration does not experience the problems of corrosion, crystallization and distillation. Furthermore, the silica gel–water adsorption system was more suitable for low grade heat source, which was confirmed by quantitatively and qualitatively comparing with a LiBr–H_2O absorption system and a desiccant air system [9]. However, this technology must confront challenges of low cooling capacity, low Specific Cooling Capacity (SCP) and low Coefficient Of Performance (COP). Therefore, many efforts on improvement of silica gel–water adsorption refrigeration technology have been done. In this paper, the working pair of silica gel–water, heat and mass transfer, new cycles and system designs, simulation work, prototype development, applications about silica gel–water adsorption refrigeration in about the last two decades are reviewed, commentated and analyzed.

2. Working pair improvement

Silica gel–water, the working pair, is vital to the adsorption cooling system as the similar function as the compressor in a vapor compression system. Silica gel is made from silicon dioxide hydrosol after sequentially undergoing the process of condensation polymerization, aging and being partially dehydrated. Silica gel is an amorphous form of silicon dioxide. Silicon atoms irregularly arrange in silica gel. Various surface functional groups including free (or isolated) silanol group, interpartical hydrogen-bonded silanol group, surface hydrogen-bonded silanol group and inner silanol group are covering on the surface of micropores in silica gel. The chemical and physical interaction of those groups can be classified into hydrogen bond, polar and weak electron transfer adsorption sites. Free silanol groups are the most activated adsorption sites on the surface of micropores in silica gel to adsorber water molecules. Therefore, the number of free silanol group will significantly influence the adsorption performance of silica gel to water. Additionally, silica gel appears in subacidity and is stable in the non-alkalescence surroundings. Therefore, suitable measures to increase the number of free silanol group and maintain acidity surroundings should be taken effectively to improve the adsorption performance of silica gel to water [10].

Surface modification is one of the most effective methods to enhance adsorption performance of silica gel–water working pair. A novel composite adsorbent with silica gel modified by calcium nitrate for utilization in an adsorption chiller driven by low-temperature heat was studied and the thermodynamic cooling COP was estimated to be 0.51–0.71 [11].

Calcium chloride ($LiCl_2$) or lithium chloride ($CaCl_2$) as well as silica gel have strong capability to adsorb water, so they can be used together in chiller as composite adsorbent. Koptyug et al. [12] used Nuclear Magnetic Resonance (NMR) microimaging technique to study water adsorption on a $CaCl_2$/silica single pellet. The promising sorption properties of this material caused a high COP of 0.6 at desorption temperature of 90–95 °C [13]. The predicted maximum COP was 0.62 when the composite adsorbent was used in a single-bed system with a half cycle time of 50 min [14]. According to Saha [15], the cooling capacity and COP of a chiller using such composite adsorbent rise up to 20% and 25% respectively. San and Hsu's [16] results illustrated that the COP and SCP of adsorbers filled with composite adsorbent of $CaCl_2$ in mesoporous silica gel (named as SWS-1L) could be increased by 51% and 38.4%, respectively, at the regeneration temperature of 120 °C. And the thermodynamic cooling using the silica gel containing 33 wt% $CaCl_2$–water as working pair showed an exciting COP of 0.83 [17]. Gong et al. [18] impregnated lithium chloride with silica gel to make into composite adsorbent. For a novel adsorption chiller using such composite adsorbent, the COP and cooling capacity are 1.43 and 5.30 kW, respectively, at the hot water inlet temperature of 80 °C, cooling water inlet temperature of 30 °C, and chilled water inlet temperature of 20 °C.

Thermodynamic characteristics of silica gel–water working pair are important to adsorption performance improvement. Ng et al. [19] described an experimental approach to detect the thermodynamic characteristics of silica gel–water working pair. The experimental results proved that Henry-type equation was more suitable to describe the isotherm characteristics of silica gel–water working pair in an adsorption chiller.

The stability and adsorption performance degradation of silica gel to water have aroused the researchers' attention. Henninger et al. [20] presented their results on the stability of silica gels. A slightly reduced water uptake of about 5% had been observed according to their experimental data and they pointed out that this loss must be further investigated. Wang et al. [10] studied the factors to influence the adsorption performance degradation in silica gel–water adsorption refrigeration and concluded that pollution caused by impurity ions and solid particles was the primary factor to decline the adsorption capacity.

Aforementioned research about silica gel–water working pair indicates that making composite adsorbent of silica gel is one

method effectively to enhance the adsorption performance of silica gel to water and the adsorption performance degradation of silica gel to water should be considered when the silica gel–water adsorption chillers are used for the industrial and commercial purposes. The main methods of the working pair improvement are listed in Table 1.

Table 1
Summary of working pair improvement with modification.

Composite adsorbent	Results	Reference
Silica gel/calcium nitrate	COP: 0.51–0.71	[11]
Silica gel/calcium chloride	COP: 0.6 at desorption temperature of 90–95 °C	[13]
	COP: 0.62	[14]
	COP and SCP: up to 20% and 25%	[15]
	COP and SCP: increased by 51% and 38.4%	[16]
	COP: 0.83	[17]
Silica gel/lithium chloride	COP and cooling capacity: 1.43 and 5.30 kW	[18]

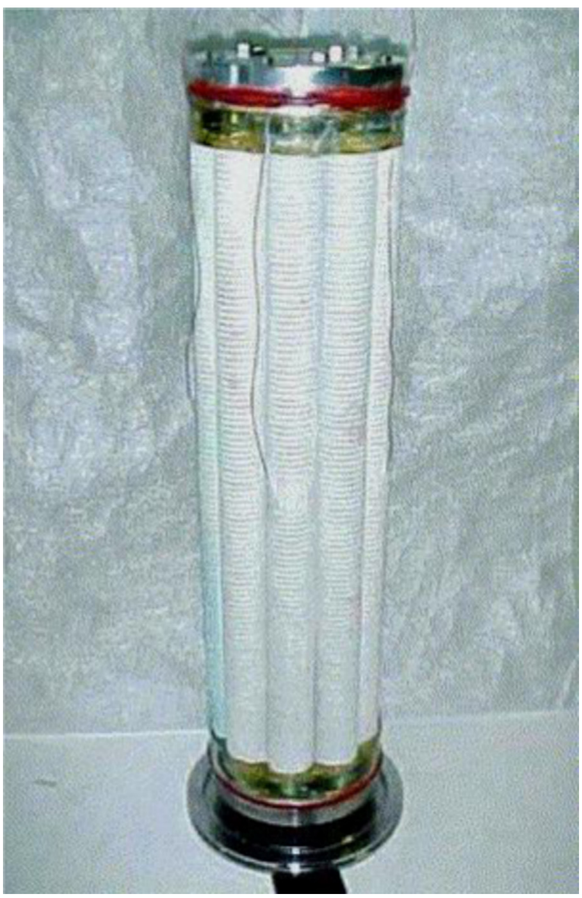

Fig. 1. Finned tubes heat exchanger coated with composite silica gel with $CaCl_2$ [26].

3. Heat and mass transfer

Heat and mass transfer performance of adsorber is also vital to an adsorption refrigeration system. The adsorbent, silica gel, is porous with small thermal conductivity as the same as thermal insulating materials. The main resistance of heat and mass transfer is in adsorbent side of an adsorber. Heat and mass transfer are commonly contradictory to each other in adsorbers. Therefore, suitable measures should be taken for the requirements of both heat and mass transfer performance. In water-evaporating adsorption refrigeration, the pressure of water vapor is quite low. It is disadvantageous to mass transfer in adsorbers. Therefore few methods can be adopted to enhance the mass transfer of water in silica gel packed adsorbers except thinning the thickness of the silica gel layer. Many efforts have been done for heat transfer enhancement of the silica gel packed adsorbers without declining the present mass transfer performance. The following description mainly focuses on heat transfer enhancement methods that are categorized into working pair enhancement and optimizing adsorber design.

3.1. Heat and mass transfer enhancement of working pairs

Adsorbers filled with silica gel granules are usually adopted by researchers at present because of their good mass transfer performance and simpler configurations. Aristov et al. [21] studied the dynamic adsorption performance of simple configuration bed with different layers of loose silica gel granules and found that the specific power reduced with increasing of the granule size when granule size was larger than 0.8 mm.

Additionally, additives with higher heat and mass transfer performance are commonly used to enhance heat and mass transfer performance of silica gel–water working pair. Without effects on the equilibrium adsorption amount of water in silica gel, expanded graphite in the composite blocks led to thermal conductivity higher than 10 $W m^{-1} K^{-1}$ and permeability larger than 10^{-12} m^2 [22]. Performance of the cooling system using graphite/silica-gel composite blocks with good mass and heat transfer was enhanced [23]. One great potential composite adsorbent synthesized from activated carbon, silica-gel and $CaCl_2$ was tested too [24]. This kind of composite adsorbent showed the best adsorption performance at low pressure that can adsorb 0.23 g water per gram of the dry adsorbent at 900 Pa. However, its mass and heat transfer performance need further study.

Heat and mass transfer resistance of inter-particle and intra-particle in silica gel granules packed adsorber are different. At low temperature, the specific volume of water vapor is quite large so

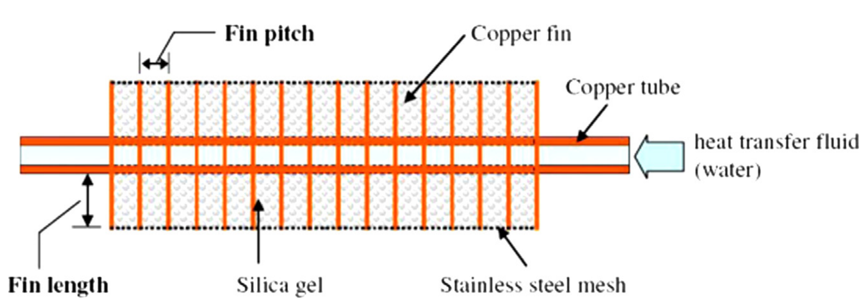

Fig. 2. Schematic diagram of fin tube module packed with silica gel granules [30].

that the flow velocity of water vapor among silica gel particles is very high in the adsorption process. As a result, the intra-particle mass transfer resistance enlarges. Solmuş et al. [25] pointed out that efforts should be focused on reducing heat transfer resistances and intra-particle mass transfer resistances but not inter-particle mass transfer resistances in order to improve the performance of the adsorber.

3.2. Heat and mass transfer enhancement of adsorber

Though an adsorber filled with silica gel granules seems good mass transfer performance, the adsorber coated with silica gel attracts more interest of researchers because of its high heat transfer as well as high mass transfer. In order to coat silica gel into metal surfaces of adsorber, the processes of mixing, pasting and drying are necessary. At first, the silica gel or composite adsorbent with silica gel is usually mixed with a certain binder. Then the mixture is pasted on the metal surfaces. Finally the metal pasted with the mixture is dried in a given temperature and the adsorbent layer is tightly stuck on the surfaces.

Certainly, the contact thermal resistance will greatly decline if the silica gel granules are coated on the metal surfaces. Freni et al. [26] coated a compact layer of composite silica gel with $CaCl_2$ and bentonite clay (33.7 and 25 wt%) onto a heat exchanger (as shown in Fig. 1) which was used in an advanced solid adsorption chiller and the tested SCP was 150–200 W/kg adsorbent. A novel calorimetric method to assess heat of adsorption, equilibrium, and dynamic adsorption data of Type A beaded silica gel coated on a heat exchange surface was proposed by Ahamat and Tierney [27]. Pezk et al. [28] coated the silica gel layer to the metal and then packed the silica gel granules/metal particles mixtures into the fin spaces to enhance heat and mass transfer of adsorbers.

In order to enhance heat and mass transfer rates of the adsorber, Li et al. [29,30] developed a fin-type silica gel tube module that was circular finned-tube heat exchanger with silica gel packed between the fins, as shown in Fig. 2. But the experimental results were not satisfying. The maximum COP was only about 0.3 when inlet temperatures of chilled water, cooling water and hot water were 15 °C, 30 °C and 80 °C, respectively.

Hamid et al. [31] considered both inter-particle and intra-particle mass transfer resistances and investigated effects of fin height and spacing on SCP and COP for beds with annular and square plate fins. According to the analytical investigation of Khan et al. [32], the performance of a re-heat two-stage silica gel–water adsorption chiller was obviously influenced by thermal capacitance ratio and overall thermal conductance ratio. The influence of heat exchanger heat capacity and Number of heat Transfer Units (NTU), on the optimum performance of a single-stage adsorption chiller was investigated by Miyazaki et al. [33]. Alam et al. [34] numerically investigated the influence of NTU, bed Biot number (Bi), the heat exchanger aspect ratio (Ar) and the ratio of fluid channel radius to the adsorbent thickness (Hr), on the system performance and then concluded that the optimum switching frequency was directly proportional to NTU, Hr and conversely to Bi and Ar.

Farid et al. [35] pointed out that the cooling capacity could be improved up to 10.78% while the cooling water temperature was at 20 °C for a two-stage four-bed adsorption chiller with different

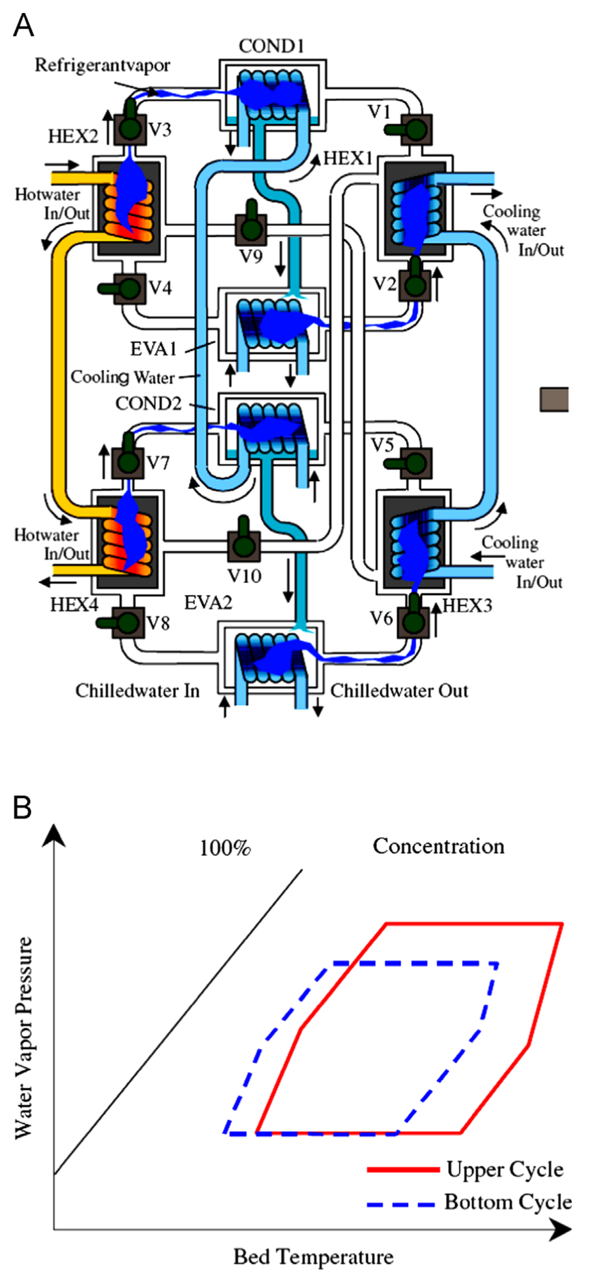

Fig. 3. Four-bed two-stage silica gel–water adsorption refrigeration cycle [44] (A) system diagram and (B) Dühring diagram.

Table 2
Summary of heat and mass transfer enhancement.

Method	Description	Reference
Enhancement of working pairs	• Silica gel, expanded graphite in the composite blocks	[22]
	• Graphite/silica-gel composite blocks	[23]
	• Composite adsorbent synthesized from activated carbon, silica-gel and $CaCl_2$	[24]
Enhancement of adsorber	• Compact layer onto coated a heat exchanger	[26–28]
	• Fin-type silica gel tube module	[29,30]

mass allocation between upper and lower beds employing the re-heat scheme. When the optimum allocation of adsorbent (water) mass was to the bottom beds in a two-stage cycle, the cooling capacity can be improved up to 20% but COP was less significantly improved [36].

The main measurement of the heat and mass transfer enhancement are summarized in Table 2.

4. Cycle and system designs

Besides basic and typical two-bed adsorption refrigeration cycles, other cycles with multi-bed, multi-stage, cascading, heat and mass recovery etc. are all attracting peoples' attention. Basic adsorption cycle is seldom used for silica gel–water adsorption refrigeration due to just one adsorber in intermittently working per cycle. Typical two-bed cycle can continuously yield refrigeration output and was widely adopted before other improved cycles emerged [37–39] and even popularly used today. Cho and Kim [37] theoretically and experimentally studied a two-bed silica gel/water adsorption cooling cycle for the recovery of a low-grade waste heat with its cooling capacity of about 4 kW and chilled water supply at 4–7 °C.

4.1. Heat and mass recovery cycles

Heat and mass recovery cycles are easily fulfilled based on one typical two-bed adsorption cycle. A passive heat recovery scheme was proposed by Wang et al. [40,41]. In this scheme, the cooing water flows into hot water reservoir after cooling the hot adsorber and the hot water flows into cooling tower after heating cool adsorber during the switching process without additional pumping action or valves. As the results [40], the COPs of a two-bed chiller and a four-bed chiller were improved by as much as 38% and 25%, respectively, and there was almost no effect on the cooling capacities. The highest COPs achieved with a two-bed and four-bed chillers were about 0.46 and 0.45, respectively. Their other report [41] showed that the passive heat-recovery scheme had the same efficiency as the Nishiyodo water-circulation heat-recovery scheme. Mass recovery cycles with or without heating and cooling are both effective. The simulation and experimental results [42,43] showed that SCP of mass recovery cycle was improved and lower

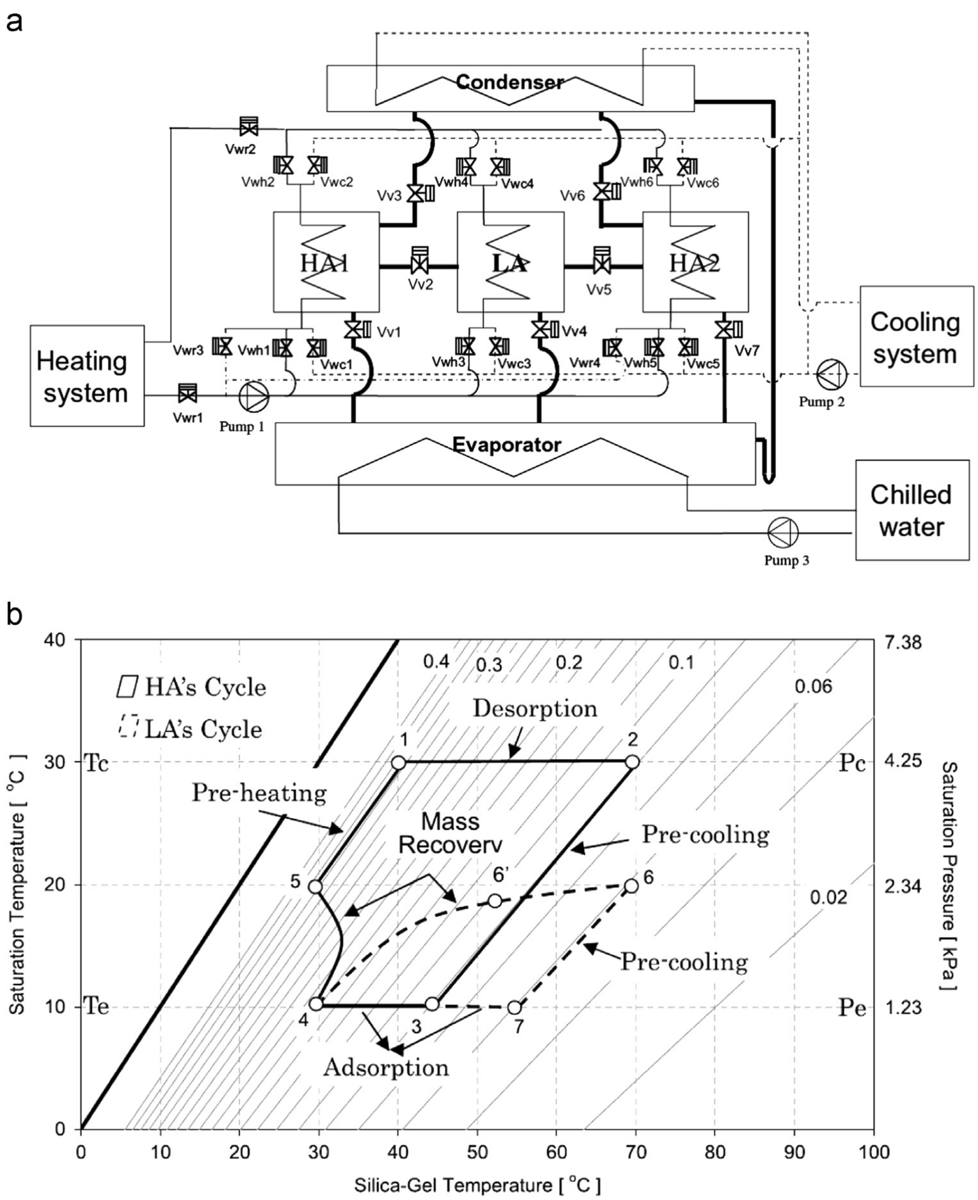

Fig. 4. Three-bed silica gel–water adsorption refrigeration cycle [45] (a) system diagram and (b) Dühring diagram.

temperature heat source can be used compared with a conventional cycle. For a four-bed two-stage cycle (as shown in Fig. 3) [44], mass recovery cycles were better than a conventional single-stage cycle for a low heat source temperature and the cascaded chilled water flow was better than the parallel chilled water flow.

Uyun et al. [45] introduced an adsorption cycle, advanced three-bed mass recovery cycle as shown in Fig. 4. The mass recovery between the two beds is at the same pressure level from the beginning to the end while one bed is heated and the other is cooled. The estimated performance of the proposed cycle was better than that of a single stage and mass recovery cycle, but the cycles with and without heat recovery had different effectiveness that heat recovery was better for COP but not for SCP.

4.2. Cascading cycle

A novel cascading adsorption cooling cycle was proposed by Liu and Leong [46], as shown in Fig. 5. This cycle comprised two zeolite adsorbers driven as the high temperature stage and a silica gel adsorbers as the low temperature stage. A lumped model was assumed for this cascading cycle. The simulated COP was up to 1.35 under the condition at generation temperature for zeolite of 200 °C and for silica gel of 100 °C, condensing temperature of 25 °C and evaporating temperature of 5 °C.

4.3. Multi-bed multi-stage cycles

Three-stage silica gel water adsorption refrigeration cycle was proposed [47,48]. This cycle can be operated by smaller regenerating temperature lift (difference between heat source temperature and heat sink temperature), of which the lowest was about 12 °C. Khan et al. [49] simulated the performance of a three-stage six-bed adsorption chiller employing re-heat scheme (as shown in Fig. 6) that can be powered by 50–70 °C heat source at 30 °C coolant temperature. And the performance of the chiller with re-heat scheme was better than that without re-heat scheme [47,48].

In order to utilize further lower temperature heat source, a multi-bed multi-stage adsorption chiller that can be switched into different modes depending on the driving heat source temperature. In the three-stage mode, heat source at lower than 42 °C can be used [50]. Another multi-stage six-bed adsorption chiller that can be working in different operation modes was promoted and evaluated [51,52]. But the performance of this cycle was too poor to be used in a commercial scene.

4.4. Suction-pump-assisted cycle

Hirota et al. [4] proposed a suction-pump-assisted thermal and electrical hybrid adsorption heat pump in which the water vapor transportation between the adsorber and the evaporator/condenser was promoted by a mechanical booster pump, as shown in Fig. 7. The examined cooling output was 1.6 times that of the thermally operated adsorption heat pump.

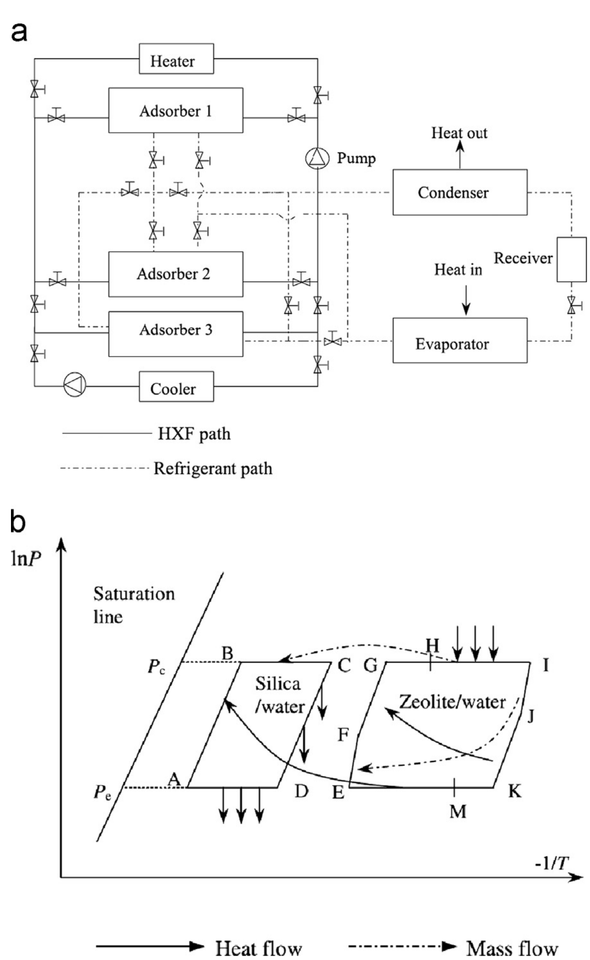

Fig. 5. Cascading silica gel–water adsorption refrigeration cycle [46] (a) system diagram and (b) Dühring diagram.

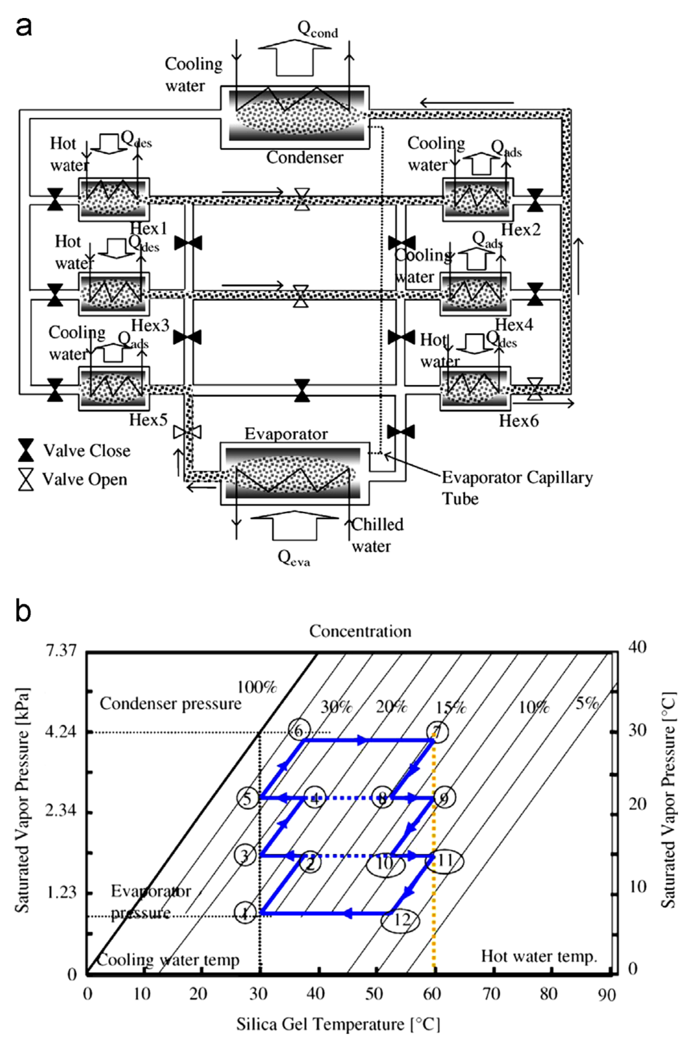

Fig. 6. Three stage silica gel–water adsorption refrigeration cycle [49] (a) system diagram and (b) Dühring diagram.

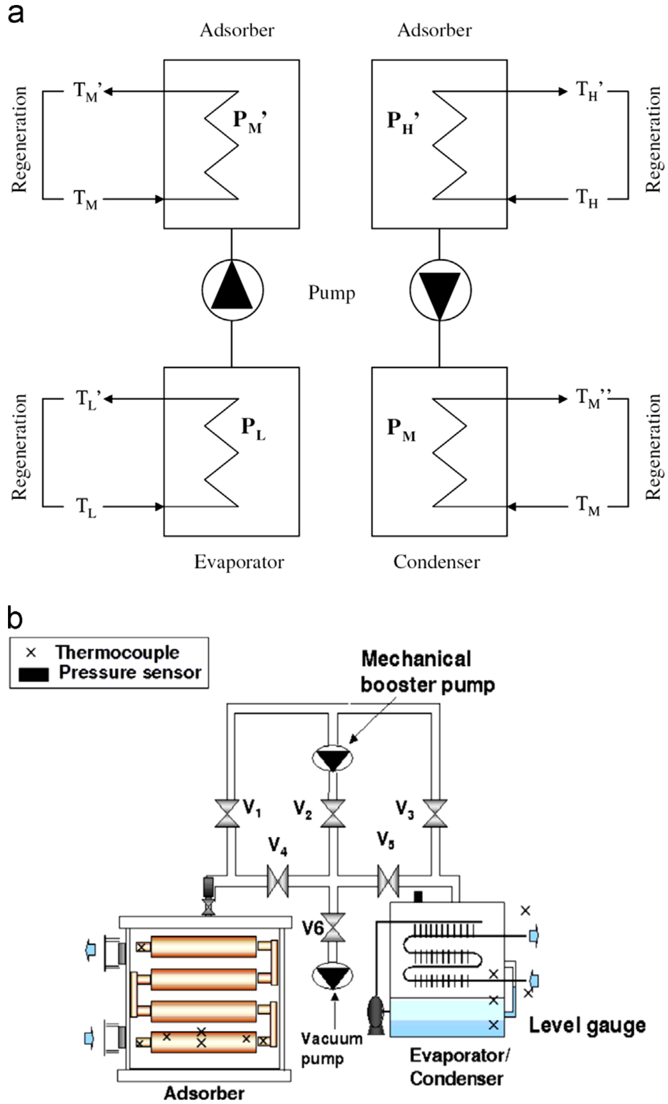

Fig. 7. Suction-pump-assisted silica gel–water adsorption refrigeration cycle [4] (a) elementary diagram and (b) system diagram.

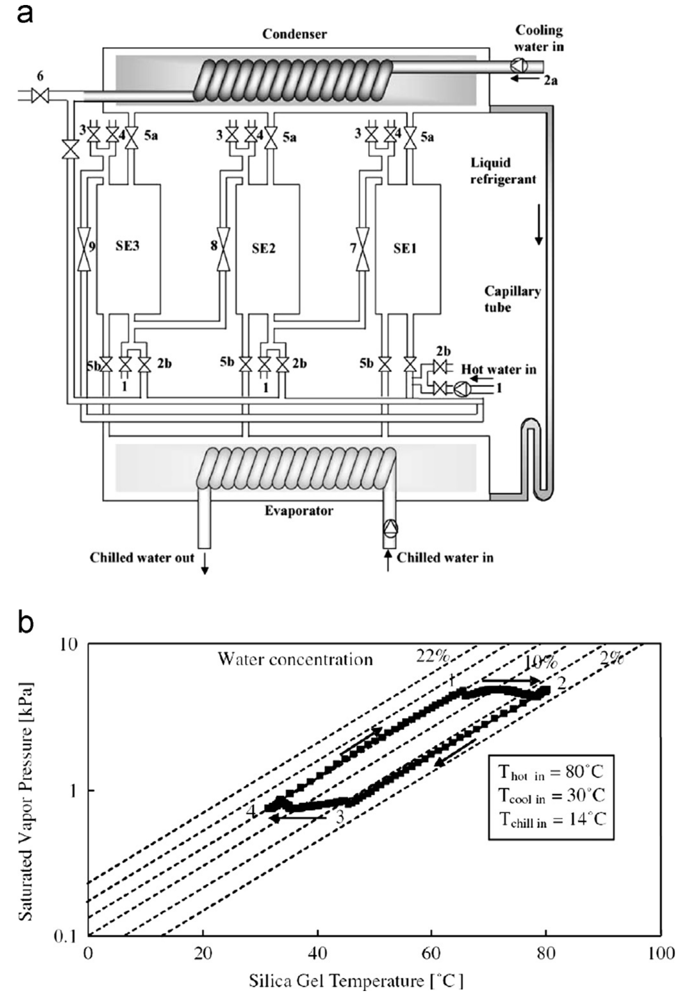

Fig. 8. Three-bed silica gel–water adsorption refrigeration cycle [53] (a) system diagram and (b) Dühring diagram.

4.5. Other research on cycles and designs

For the purpose of decrease of chilled water temperature fluctuation and driving heat source temperature (between 60 and 95 °C with a coolant at 30 °C), a three-bed adsorption cycle was recommended [53], as shown in Fig. 8. Another choice of minimizing the chilled water temperature fluctuation would be a multi-bed regenerative adsorption cycle [54]. The risk of ice formation in the evaporator during stat up reduced because of the sequential operation of the beds. A six-bed cycle generated 40% more cooling capacity than that of a four-bed cycle, while a four-bed cycle achieved 70% more than a traditional double-bed cycle. Miyazaki et al. [55] thought that the new cycle time allocation could not only improve the cooling capacity and COP, but also reduce the delivered chilled water fluctuations. Table 3 shows the summary of cycle and system designs mentioned above.

5. Simulation work

Instead of experimental study, simulation is necessary for the design of a new adsorption cooling system and its experimental preparation. Almost all new cycles, new designs and new characteristic investigations of silica gel–water adsorption cooling systems are simulated. In order to develop or improve mathematical models, many efforts have been done.

Firstly, a cyclic-steady-state model was introduced to predict the performance of silica gel–water adsorption refrigeration cycle [56,57]. In order to improve the accuracy of the cyclic-steady-state model, Chua et al. [58] proposed a transient lumped-parameter model that can be used to conduct the effects of switching and cycle times on a two-bed silica gel–water adsorption chiller. And then a transient distributed-parameter model was carried out and its higher accuracy was verified [59]. Wang and Chua [60] used an improved lump-parameter design model to investigate water-circulation heat recovery scheme and then proposed a useful and rapid design tool for the industry whose deviation was typically less than 10%. Ei-Sharkawy [61] improved a classical Linear Driving Force (LDF) model considering the dependency of the particle mass transfer coefficient on the dimensionless time to estimate the performance of adsorption chiller using composite adsorbent of $CaCl_2$ and silica gel/water working pairs. And good agreement with Fickian Diffusion (FD) model was achieved.

Alam et al. [62] proposed a novel simulation technique involving a profit function to estimate the optimum cycle time of an adsorption cooling system. A method of arriving at the minimum desorption temperature was put forward [63]. The particle swarm optimization method and the mathematical dimensionless parameters model of the adsorption chiller were developed to determine the optimum cycle time [33].

Voyiatzis et al. [64] developed a new mathematical model composed of fully non-dimensionalized governing equations to study the relationship between the switching frequency and the performance of a novel adsorption chiller. A novel empirical lumped analytical simulation model for a commercial 450 kW two-bed silica gel/water adsorption chiller incorporating mass and heat recovery schemes was developed that can be used as an evaluation and optimization tool to estimate the effects of changing fin spacing and generation temperature on chiller performance as well as the optimum cycle time [65].

Hamid et al. [66] developed a transient three-dimensional numerical scheme in which the mass transfer resistance between the particles as well as that of the intraparticle was considered. It can be used to well predict effects of fin height and spacing on SCP and COP, and the appropriate fin shape and configuration for given working conditions of a silica gel–water adsorption chiller. A design procedure was proposed to configure the specifications of an adsorbent bed for a given application [66]. Niazmand and Dabzadeh [67] presented a transient two-dimensional numerical model that can predict the effects of fin spacing, bed height, and particle size on the performance of the cylindrical bed with annular fins.

An accurate model coupled heat and mass transfer to simulate dynamic features of the Adsorption Heat Transformation (AHT) units packed with loose adsorbent granules was developed [68]. Using this model, the specific cooling capacity of AHT cycle can be estimated and the cycle dynamic optimization recommendations can be made. Distributions of the temperature and vapor concentration of vapor and solid phases can be obtained.

Santori et al. [69] developed a dynamic multi-level transient model used to simulate a solar-driven adsorption cooling system to ascertain its feasibility and be used to fulfill its performance optimization. Solmus et al. [70,71] developed one transient two-dimensional local thermal non-equilibrium model. In this model, the local volume averaging method was employed, and the external (inter-particle) and internal (intra-particle) mass transfer resistances are considered.

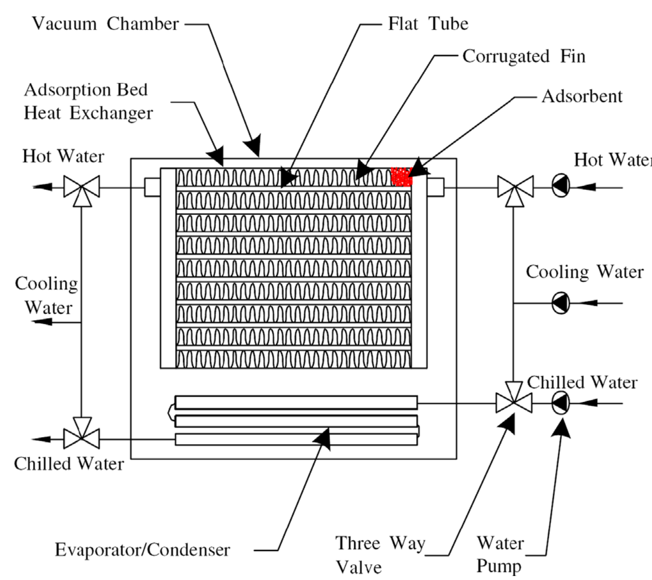

Fig. 9. One-bed silica gel–water adsorption chiller [72].

Table 3
Summary of cycle and system designs.

Enhancement	Methods	Reference
Heat and mass recovery cycles	Passive heat recovery scheme	[40,41]
	Mass recovery cycle	[42–44]
	Advanced three-bed mass recovery cycle	[45]
Cascading cycle	High temperature stage: zeolite	[46]
	Low temperature stage: silica gel	
Multi-bed multi-stage cycles	Three-stage	[47–49]
	Multi-bed multi-stage with different modes	[50–52]
Suction-pump-assisted cycle	Thermal and electrical hybrid cycle	[4]
Other cycle and system designs	Three-bed adsorption cycle	[53]
	Multi-bed regenerative adsorption cycle	[54]
	Six-bed cycle	[55]

Table 4
Summary of simulation work.

Models and methods	Main function	Reference
Cyclic-steady-state model	Performance prediction	[56,57]
Transient lumped-parameter model	Accuracy improvement of the cyclic-steady-state model	[58]
Transient distributed-parameter model	Accuracy improvement	[59]
Improved lump-parameter design model	Rapid design tool	[60]
Classical Linear Driving Force (LDF) model	Performance prediction	[61]
Novel simulation technique with a profit function model	Optimum cycle time	[62]
Particle swarm optimization method and the mathematical dimensionless parameter model	Optimum cycle time	[33]
Fully non-dimensionalized governing equations model	Optimum switching frequency	[64]
Empirical lumped analytical simulation model	Optimum adsorber structure parameters and operating parameters	[65]
Transient three-dimensional numerical scheme	Appropriate fin shape and configuration	[66]
Transient two-dimensional numerical model	Optimum adsorber structure parameters	[67]
Non-isothermal water adsorption process model	Cycle dynamic optimization Heat and mass transfer	[68]
Dynamic multi-level transient model	Performance optimization.	[69]
Transient two-dimensional local thermal non-equilibrium model	External (inter-particle) and internal (intra-particle) mass transfer resistances prediction	[70,71]

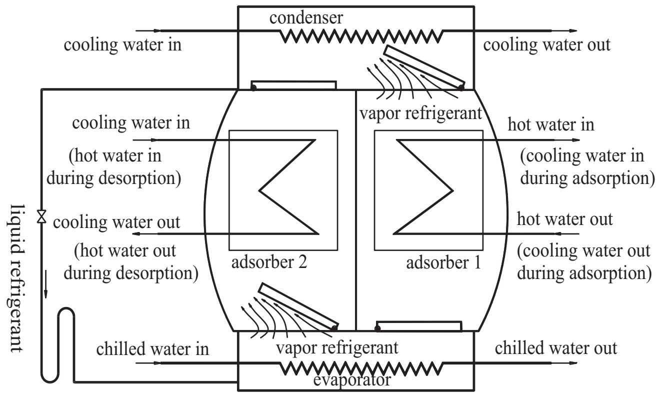

Fig. 10. Two-bed silica gel–water adsorption chiller [38,39].

All the representative simulation work about silica gel water adsorption refrigeration is listed in Table 4.

6. Prototype development

Since 1990s, many silica gel–water adsorption refrigeration prototypes were developed and manufactured. Though those prototypes were not commercial ones indeed for experiencing fundamental problems mentioned in Section 4, those efforts resulted in a closer and closer step to commercial prototypes. The silica gel–water adsorption cooling prototypes of one-bed, two-bed, multi-bed and multi-stage types were developed; hereinto two-bed prototype was the earliest and most fully-fledged one in these two decades.

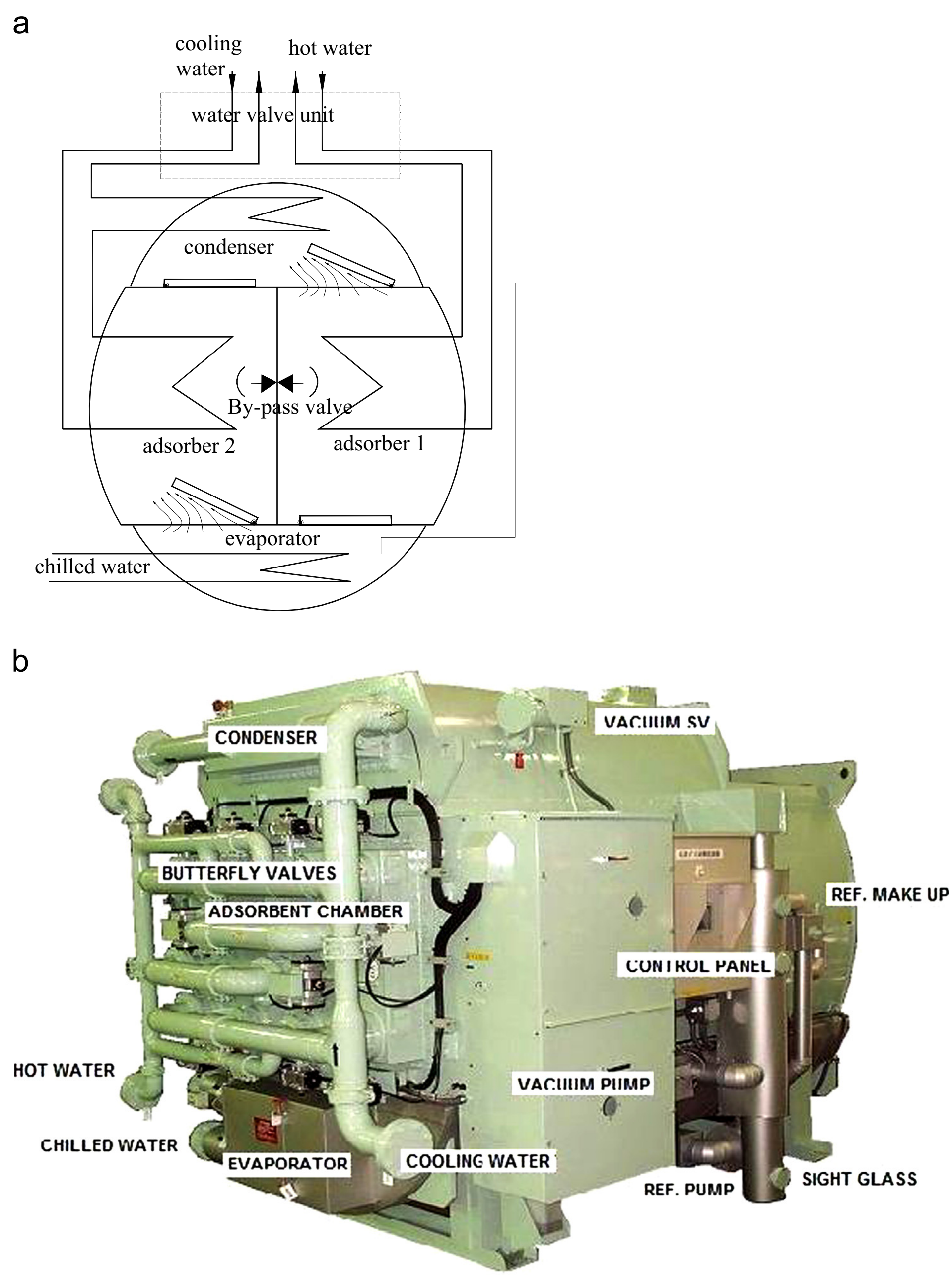

Fig. 11. Two-bed silica gel–water adsorption chiller (by HIJC USA Inc) [73] (a) schematic diagram and (b) photo.

6.1. Prototype with a one-bed system

As mentioned in Section 4, one-bed silica gel–water adsorption cycle was seldom adopted. Therefore, the development of its prototype was hardly interesting. Chang et al. [72] developed a simple structure with a vacuum tank contained an adsorption bed and an evaporator/condenser, as shown in Fig. 9. And the cooling capacity of 4.3 kW and cooling COP of 0.45 under the conditions of 80 °C hot water, 30 °C cooling water, and 14 °C chilled water inlet temperatures, were reported by them.

6.2. Prototypes with two-bed one-stage systems

Adsorption cooling cycle of a two-bed system can continuously work rather than a one-bed system and is much simpler than a multi-bed system. And the two-bed silica gel–water adsorption cooling system with heat and mass transfer recovery has high performance. As reports of Saha et al. [38,39] and website of HIJC USA Inc. [73], the cooling capacity and the COP of the chiller manufactured by NACC (Nishiyodo Air Conditioning Co. Ltd.) as shown in Fig. 10 were 12.63 kW and 0.40 respectively with the heat source temperature of 85 °C, the coolant temperature of 30 °C and the chilled water inlet temperature of 16 °C; and those of ADCM1-180 chiller manufactured by HIJC USA Inc as shown in Fig. 11 were up to 150.15 kW and 0.7 respectively when the hot water temperature was 90 °C, the coolant temperature was 29.4 °C and the chilled water temperature outlet was 7 °C. The mass recovery cycle was adopted in the chiller developed by HIJC USA Inc.

These achievements mentioned above were very exciting and valuable to the commercialization of the silica gel–water adsorption chiller. But the damp vacuum valves needed in the systems decline the reliability of those type chillers. In order to simplify the structure and remove the vacuum valves, a novel silica gel–water adsorption chiller with two adsorbers, two condensers and two evaporators was developed by Liu et al. [74], as shown in Fig. 12.

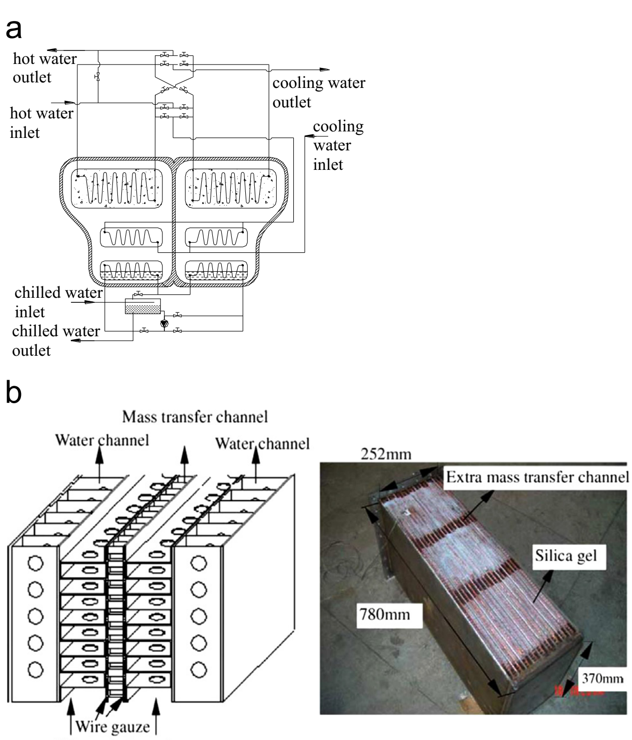

Fig. 12. Two-bed silica gel–water adsorption chiller with three vacuum chambers [74] (a) schematic diagram and (b) adsorber (diagram and photo).

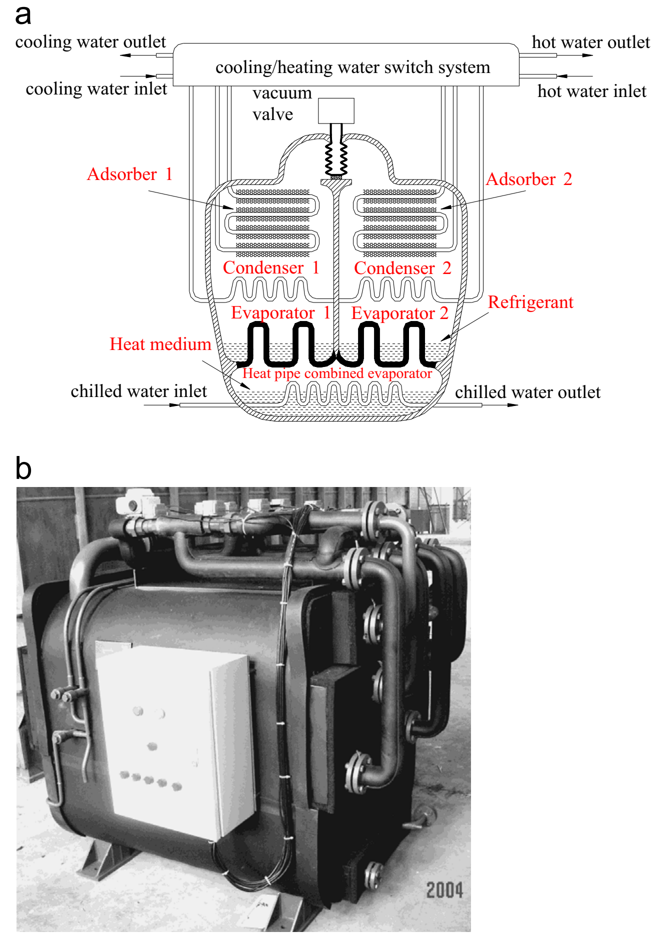

Fig. 13. Two-bed silica gel–water adsorption chiller with three vacuum chambers [76,77] (a) schematic diagram and (b) photo (from [77]).

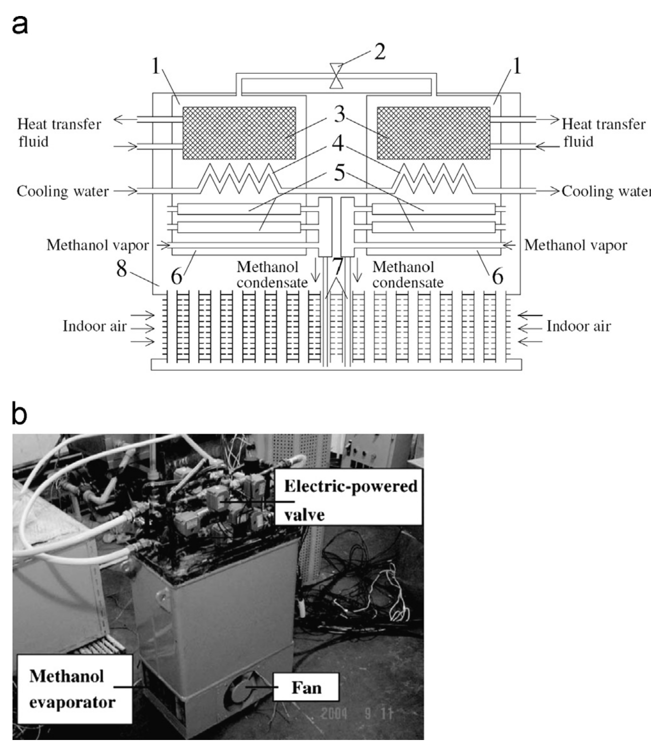

Fig. 14. Two-bed silica gel–water adsorption chiller with three vacuum chambers [80] (a) schematic diagram and (b) photo.

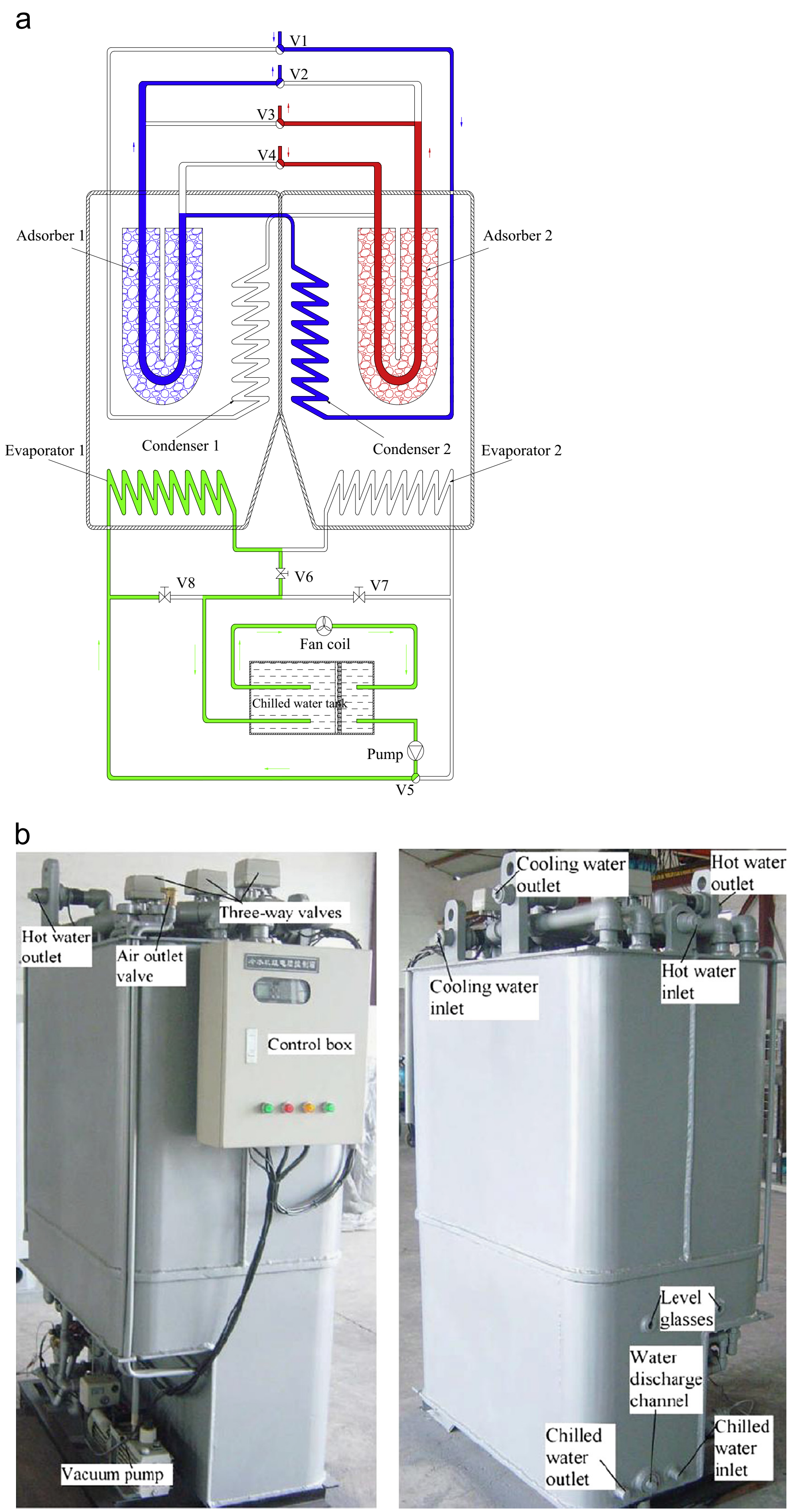

Fig. 15. Improved two-bed silica gel–water adsorption chiller with three vacuum chambers [82] (a) schematic diagram and (b) photo.

In this chiller, one adsorber, one condenser and one evaporator were housed in the same one vacuum chamber to structure as one-bed unit and two identical units was combined together with the chilled water switching system into one integrated chiller. There were no vacuum valves installed in the chiller. But the performance of this chiller was heavily impacted by the chilled water switching system due to the cooling loss caused by the sensible heat of the chilled water in switching system. The experimental results illuminated that the COP was about 0.36 at hot water temperature of 85 °C, the chilled water inlet temperature of 14 °C and the cooling water temperature of 30 °C. Other similar system with two identical modules was also developed [75]. Each module contains one adsorber and a heat exchanger for evaporation and condensation of water. Each module was one single-bed adsorption cooling unit too. The adsorption and desorption process of each module was also determined by the hydraulic switching unit. The promising test results showed that heating COP was higher than 1.5 and cooling COP was 0.5 for air-conditioning purposes (12–15 °C).

In order to improve the two-chamber system developed by Liu, Wang et al. developed another novel and simple silica gel–water adsorption chiller [76,77], as shown in Fig. 13. This chiller consisted of three vacuum chambers: two adsorption/desorption working chambers and one heat pipe working chamber. The adsorption/desorption working chamber had the same configure as the unit in the chiller developed by Liu's [74]. The effective heat pipe was used in this chiller as the switcher of two water evaporators in those two adsorption/desorption working chambers. The water evaporators were integrated and combined by the heat pipe working chamber. The test results [78] showed that the cooling capacity will reach 6 kW under the conditions of 65 °C hot water temperature, 30.5 °C cooling water temperature and 17.6 °C chilled water outlet temperature, and the COP was about 0.37 under the same working conditions. A new prototype of this type adsorption chiller was reported by Lu et al. [79]. The cooling capacity and COP were 17.9 kW and 0.63 respectively at the hot water inlet temperature of 79 °C, cooling water inlet temperature of 25.4 °C and chilled water outlet temperature of 13.7 °C. In order to utilize this type chiller into residential air conditioning, a novel small scale compact adsorption room air conditioner (as shown in Fig. 14) with dimensions of 300 mm (depth) × 500 mm (width) × 950 mm (height) has been experimentally investigated [80]. For this prototype, under typical air conditioning conditions the cooling capacity and COP were 718.5 W and 0.321, respectively.

Hereafter, many efforts have been made to improve such type silica gel–water adsorption chiller. Another compact silica gel–water adsorption chiller without vacuum valves (as shown in Fig. 15) was designed and experimentally studied by Chen et al. [81,82]. Their simulated cooling capacity and COP were 10.76 kW and 0.51 respectively and the experimental cooling capacity and COP were 9.60 kW and 0.49 respectively at a similar working condition. In order to overcome the drawback of refrigerant unbalance in the two adsorption units [76], Lu et al. [83] developed a novel silica gel–water adsorption chiller with self-balance device of refrigerant, as shown in Fig. 16. The self-balance device of refrigerant (see Fig. 16b) declined the impact of heating source temperature fluctuation on the performance of the chiller. The cooling capacity and COP of this chiller were 3.6 kW and 0.32, respectively, at the hot water inlet temperature of 57 °C, cooling water inlet temperature of 27 °C and chilled water outlet temperature of 15 °C. And those were up to 5.7 kW and 0.41 respectively when the hot water inlet temperature, cooling water inlet temperature changed to 80 °C and 29 °C, respectively.

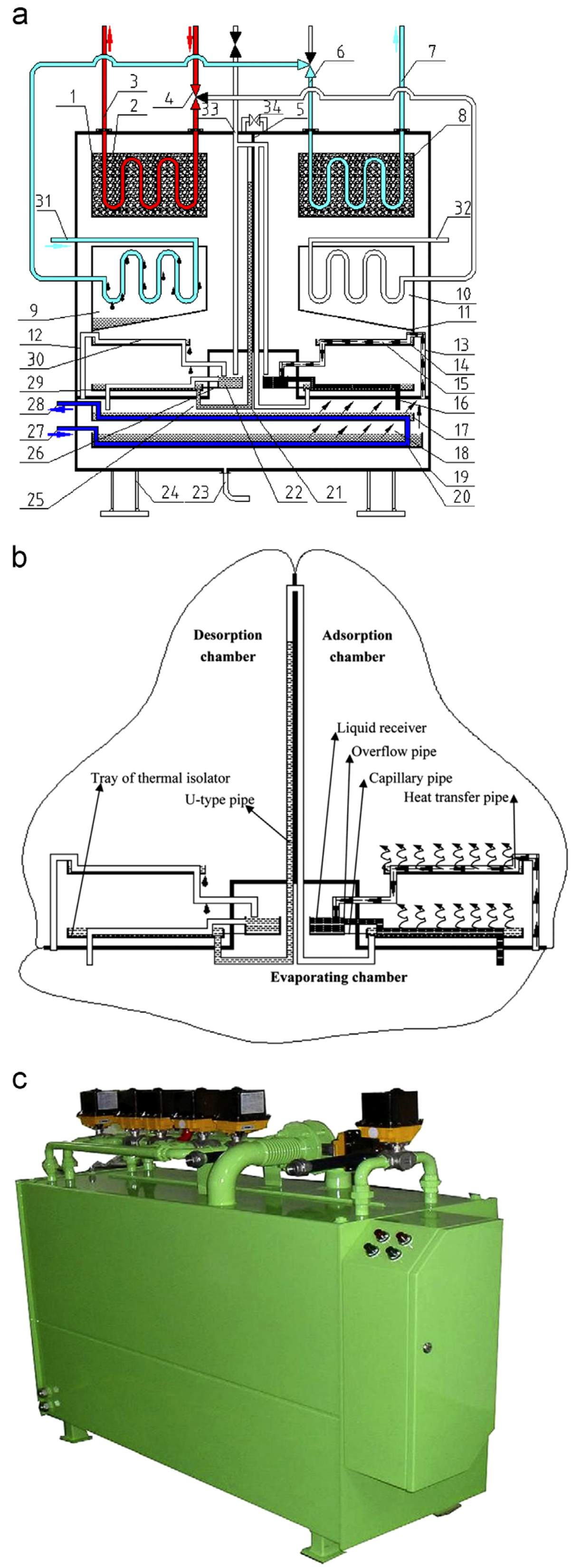

Fig. 16. Improved two-bed silica gel–water adsorption chiller with self-balancing device [83] (a) schematic diagram of chiller, (b) self-balancing device and (c) photo of chiller.

6.3. Prototypes with multi-stage systems

Multi-stage silica gel–water adsorption refrigeration chillers would be a good choice to use low grade heat source so that multi-stage prototypes were also developed though those prototypes had low performance because of being powered by low grade heat source. In 2001, a two-stage adsorption chiller prototype (as shown in Fig. 17) was reported [84], whose COP was about 0.36 with a driving source at

55 °C and a heat sink at 30 °C. A three-stage silica gel–water adsorption prototype, as shown in Fig. 18, was reported by Saha et al. [52]. The aim of this design was to utilize the heat sources at 40–95 °C with different operation modes. But no experimental data about this prototype were reported.

The performance of the developed prototypes is shown in Table 5.

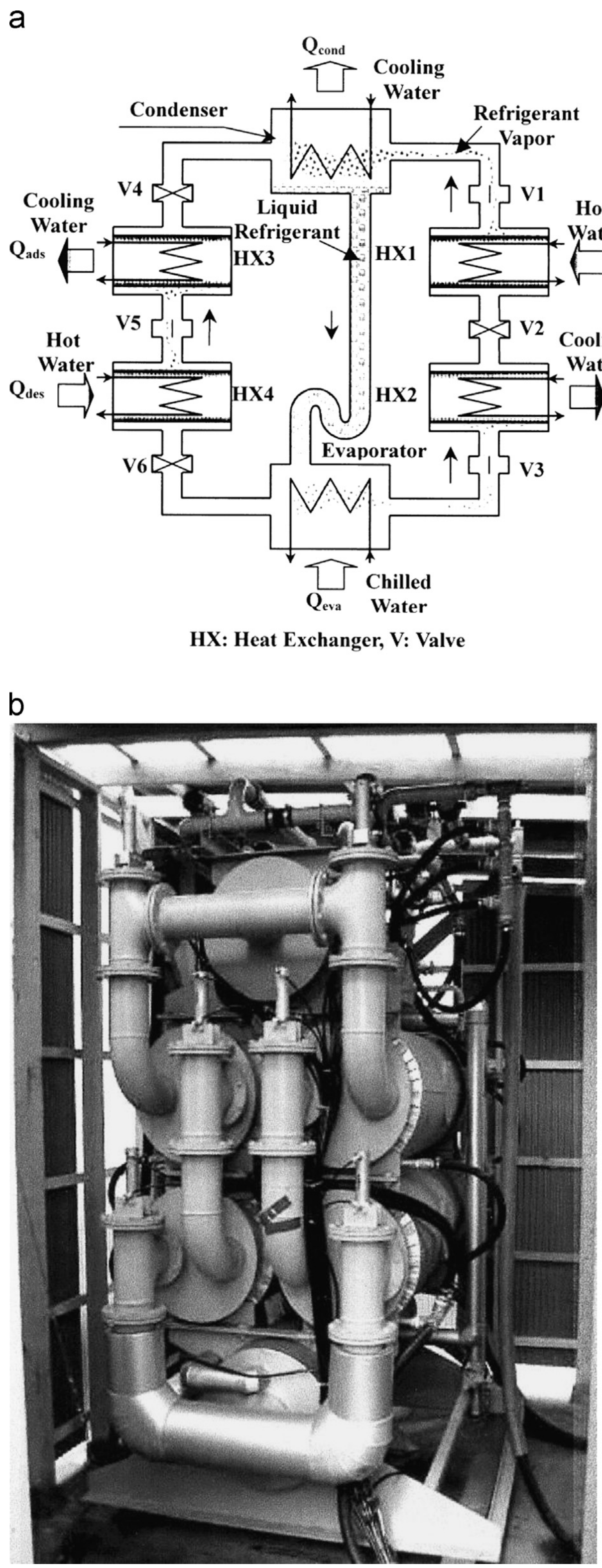

Fig. 17. Two-stage silica gel–water adsorption chiller [84] (a) schematic diagram and (b) photo.

7. Study of practical applications

Application of the silica gel–water adsorption refrigeration technology is one effective method to find technical problems ignored during design in office and test in lab as well as to detect the reliability of the chiller, which is quite different from lab investigation. Many researchers and engineers have studied the applications of silica gel–water refrigeration systems including variable heat source efficiency, solar utilization, and Combined Cooling, Heating and Power (CCHP) system.

7.1. Unstable heat source

Unstable heat source is not avoided when a silica gel–water adsorption cooling setup is used in a practical system especially being driven by solar energy. The unstable heat source, as a driving

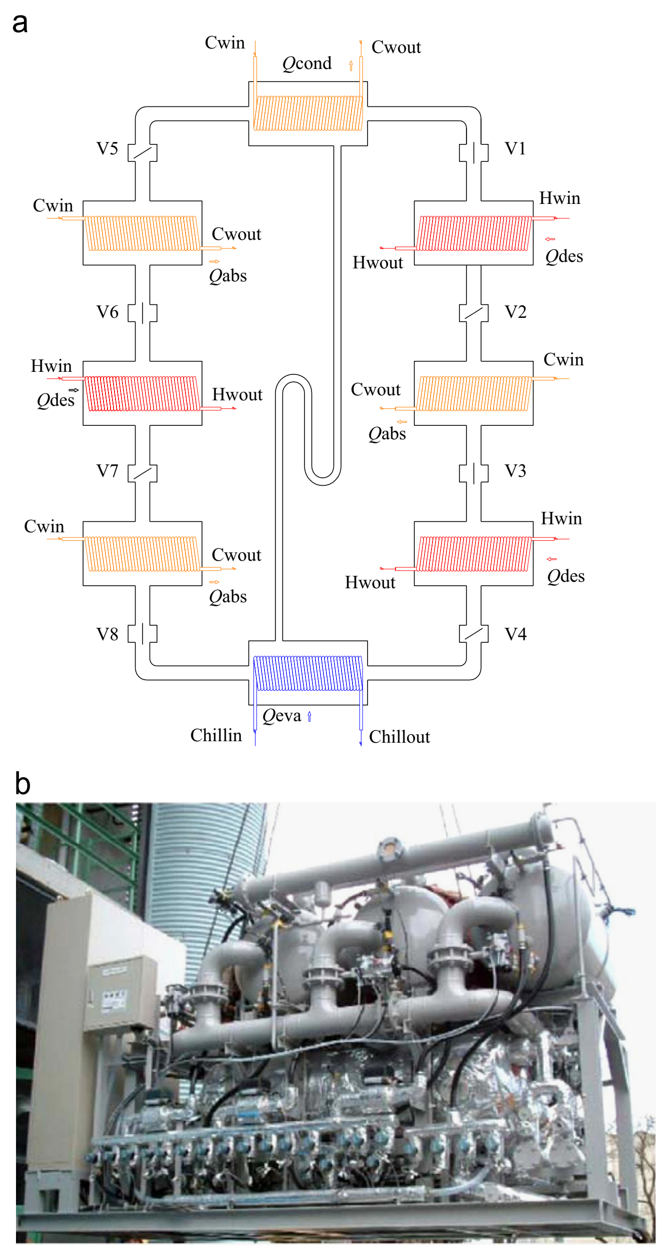

Fig. 18. Three-stage silica gel–water adsorption chiller [52] (a) schematic diagram and (b) photo.

force of an adsorption system, must influence the dynamic characteristics and performance of the adsorption chiller. Di et al. [85] studied the influence of the variation rates of the heat source temperatures on COP of the chiller. Significant impact on COP was observed and a buffer tank was considered better for weak solar irradiation but worse for high solar irradiation. Wang et al. [86] and Wu et al. [87] also proved this result and proposed the operation control strategies according to different heat source temperature. Zhang et al. [88] preferred to adopt the open circulation of the hot water with a short cycle time and the closed circulation of hot water with a longer cycle time when the chiller was driven by solar energy.

Table 5
Summary of prototype development.

Prototype	Performance					Reference
	T_h (°C)	T_c (°C)	$T_{chilled}$ (°C)	COP	Q_r (kW)	
One-bed system	80	30	14	0.45	4.3	[72]
Two-bed system	85	30	16[a]	0.40	12.6	[38,39]
	90	29.4	7	0.7	150.2	[73]
Two-bed with two-chamber system	85	30	14[a]	0.36		[74]
Two-bed with three-chamber system	65	30.5	17.6	0.37	6	[78]
	79	25.4	13.7	0.63	17.9	[79]
	80	29	15	0.41	5.7	[83]
Two-stage system	55	30	14[a]	0.36	3.2	[84]

Note: T_h hot water temperature.
T_c coolant inlet temperature.
$T_{chilled}$ chilled water temperature (outlet).
[a] The inlet temperature of the chilled water to the evaporator.

7.2. Applications in solar powered systems

Solar energy is one kind of the most favorable and popular renewable energy, and various solar energy application systems are continuously valued. Solar powered silica gel–water adsorption refrigeration is no exception. Solar powered adsorption refrigeration system can be categorized into direct utilization system and indirect utilization system. In a direct system, the adsorber is integrated with the solar collector as a whole. The adsorbers in an indirect system will be heated by medium in solar energy collection and supplying system but not by solar irradiation directly. A direct-radiation absorption collector for a silica gel and water working pair was tested by Tangkengsirisin et al. [89]. This

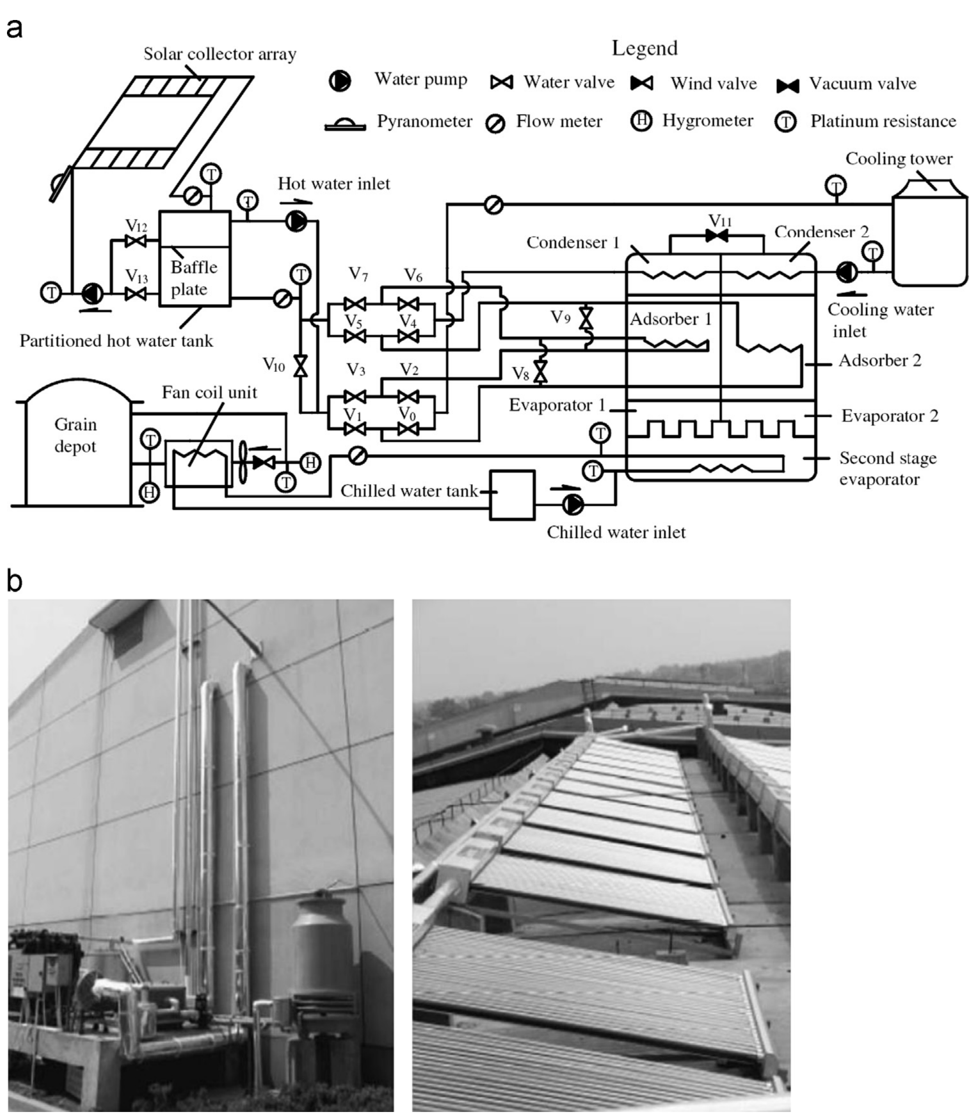

Fig. 19. Solar powered silica gel–water adsorption chiller used for grain depot cooling [91] (a) schematic diagram of the system and (b) photo.

kind of adsorber has a higher thermal efficiency but it just fits for an intermittent cycle.

Two-bed continuous silica gel–water adsorption refrigeration chiller was more popular and widely utilized in a solar-powered cooling system in recent years. Luo et al. [90,91] applied the silica gel–water adsorption chiller developed by Wang et al. [76] into a solar-powered adsorption cooling system for low-temperature grain storage, as shown in Fig. 19. Cooling capacity of this system was 3.06–4.18 kW while a daily solar cooling COP ranged between 0.1 and 0.13, and the corresponding electric cooling COP was between 2.6 and 3.4 when a daily solar radiation is 16–21 MJ/m^2. Zhai et al. [92] also used this type chiller into the solar powered adsorption air-conditioning system in the green building of Shanghai Research Institute of Building Science, as shown in Fig. 20. Two chillers were powered by 150 m^2 solar collectors. This system continuously ran from 9:00 to 17:00 in the summer of 2005 with average cooling output of 15.3 kW and the maximum value of higher than 20 kW under the representative working condition. The chiller with similar structure has also been introduced into a small scale hybrid solar heating, cooling and power generation system [93].

Another similar type adsorption chiller was used in a solar powered adsorption air conditioning [79] and under the typical summer weather conditions, the experimental average solar COP

Fig. 21. Solar powered silica gel–water adsorption chiller used for air conditioning [94].

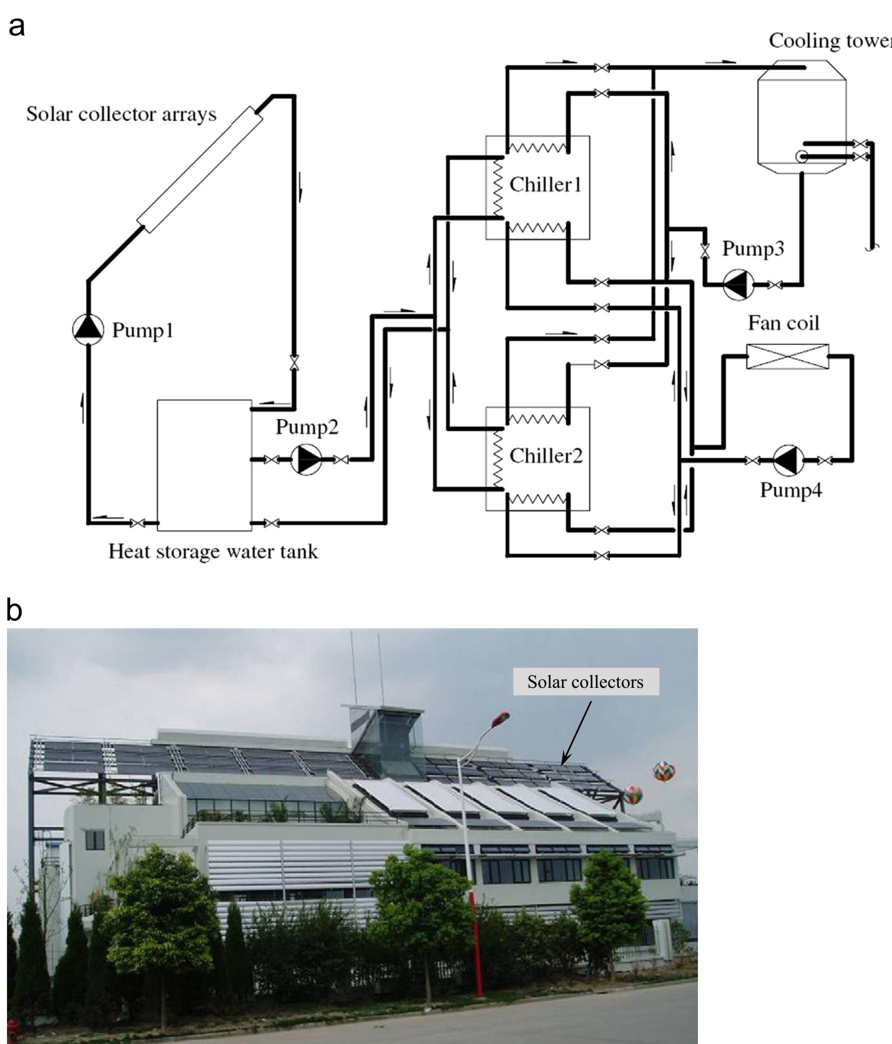

Fig. 20. Solar powered silica gel–water adsorption chiller used for green building air conditioning [92] (a) schematic diagram of the system and (b) photo of integration of solar collector arrays and the green building.

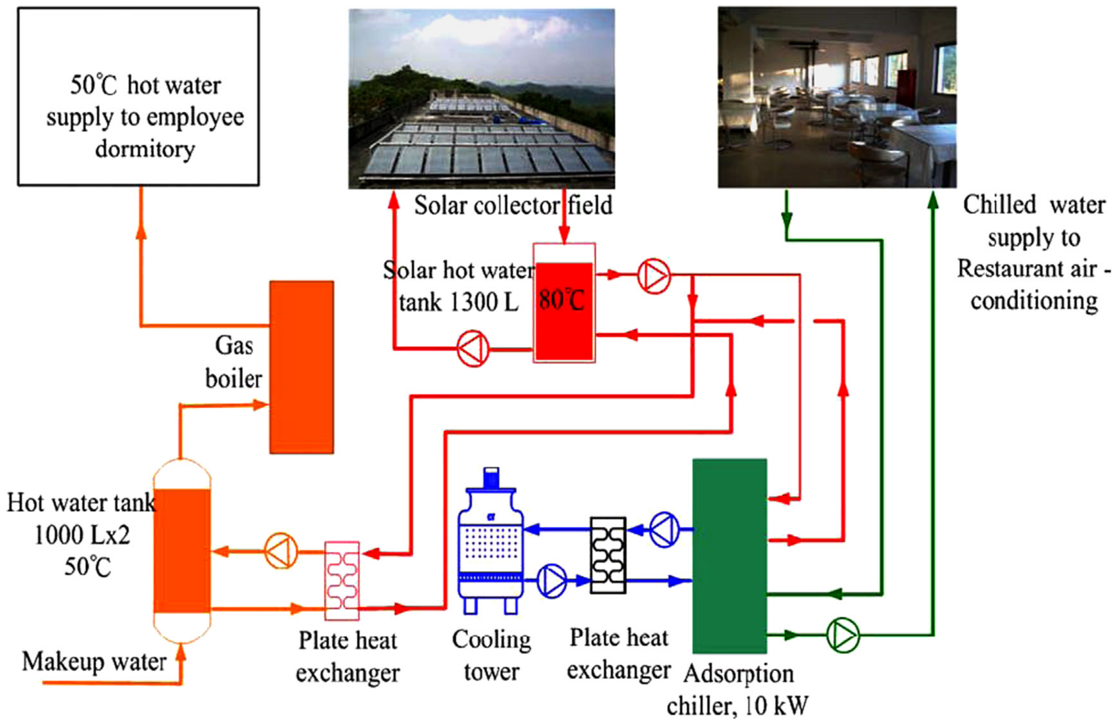

Fig. 22. Schematic diagram of the system for heating and cooling [95].

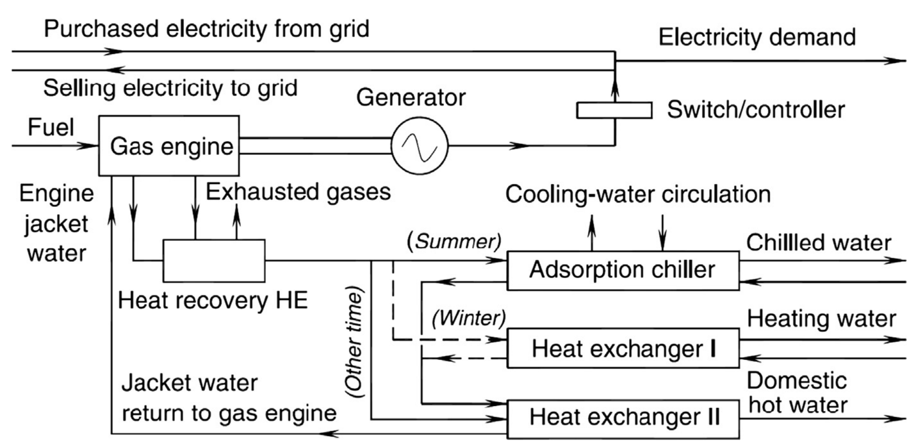

Fig. 23. Schematic diagram of the silica gel–water adsorption chiller [96].

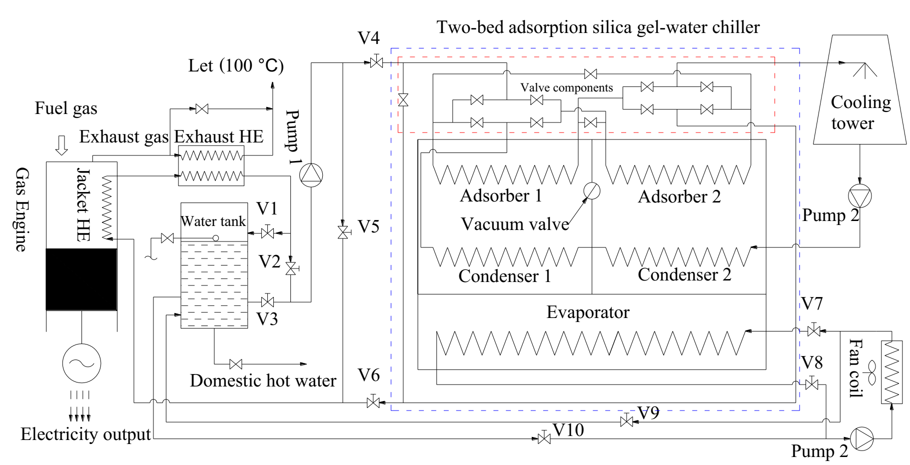

Fig. 24. Solar powered silica gel–water adsorption chiller used for air conditioning [97].

of the solar powered silica gel–water adsorption cooling system was 0.16 which was very close to the simulation results of similar system developed by Santori et al. [69], while the average COP of the adsorption chiller was 0.44. Lu et al. [94] also experimentally studied a solar powered adsorption cooling system with new compound parabolic concentrator collectors that can obtain higher temperature. The photograph of this system is shown in Fig. 21. Compared with a solar powered absorption one, the solar powered adsorption cooing system had a lower average solar COP of 0.16, but the cooling supplying time increased by 2/3. Chang et al. [95] applied a solar-powered compound system to provide air-conditioning and hot water as shown in Fig. 22, of which the typical daily efficiency was 12.8%.

7.3. Applications in combined cooling, heating and power (CCHP)

CCHP system can supply cooling, heating and power at the same time to meet the various requirements of energy consumers'. The cooling and heating energy can be produced by the waste heat of power conversion from fuel in a CCHP system so the overall energy utilization efficiency is quite high. This technology has widely used in distributed generation systems now. Theoretically and practically, absorption chiller as well as adsorption chiller can be driven by the waste heat form engine in CCHP to yield cooling. But an adsorption chiller is more recommendable rather than absorption one in view of the highlighting merits mentioned in the introduction section. Therefore, some research has been attempted for applications of silica gel–water adsorption into CCHP systems.

Fig. 25. A silica gel–water adsorption chiller employed in a CCHP system [98].

Kong et al. [96] introduced a silica gel–water adsorption chiller into a micro-CCHP system which had a nominal electricity power of 12 kW, a nominal cooling of 9 kW and a nominal heating capacity of 28 kW, as shown in Fig. 23. The investigation of the whole system showed that the overall thermal and electrical efficiency was over 70%. Li and Wu [97] introduced the same type two-bed silica gel–water adsorption chiller into a micro CCHP system (as shown in Fig. 24) and investigated the chiller performance and its improvement. The results of theirs indicated that the average cooling load, the system cycle mode and the fluctuation of electric load greatly impacted the performance of the chiller. Grisel et al. [98] developed a silica gel–water adsorption chiller that can be integrated in a prototype tri-generation (CCHP) system, as shown in Fig. 25. But this chiller was not tested in a CCHP system. Zhai et al. [93] applied a silica gel–water adsorption chiller into a small scale CCHP system that could provide both thermal energy and power for remote off-grid regions, as shown in Fig. 26. But the economical analysis in terms of cost and Payback Period (PP) was not exciting for 18 years PP under present energy price and 10 years PP when energy price increases by 50% and interest rate decreases to 3%. Because the capital expense for equipment and installation is too high and the total efficiency of the system is too low, the applications of a silica gel–water adsorption chiller in a CCHP system have been hindered.

8. Prospects and conclusions

In spite of the many efforts by researchers and engineers, silica gel–water adsorption cooling systems still experience size, performance and cost limitations owing to low heat and mass transfer performance of the adsorber, its high vacuum necessity, and its low operation reliability. Enhancement of heat and mass transfer of the adsorber will result in smaller size of adsorber and cooling system as well as lower manufacturing cost. Mixed refrigerant with water would be a good choice to reduce the high vacuum

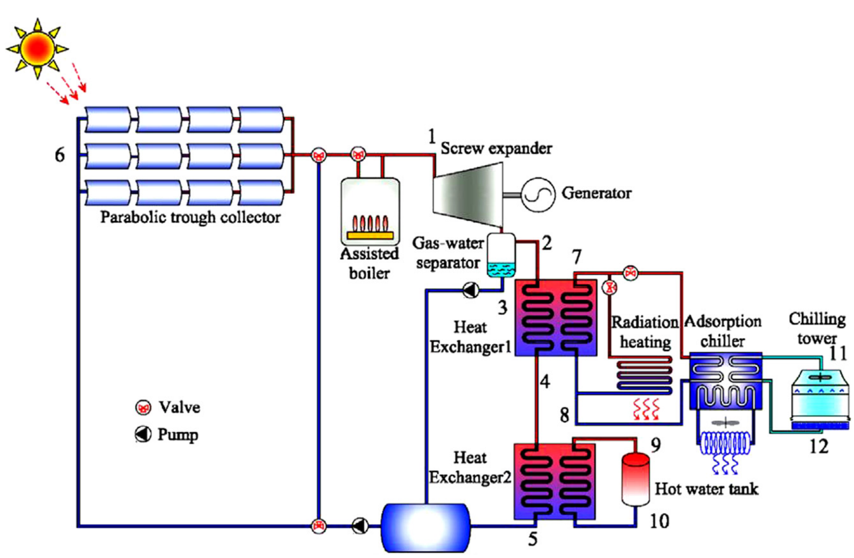

Fig. 26. CCHP system with a silica gel–water adsorption chiller [93].

requirement determined by water vapor. But there is no information available about this at present.

Indeed, there is a lot of work remaining for real commercial and industrial utilization of a silica gel–water adsorption cooling system. The solving of the aforementioned problems begins this necessary work. Besides preserving silica gel–water adsorption cooling applied to low temperature thermal energy source (<100 °C) [99,100], new adsorbent materials needed to be developed. It is exciting that some research has investigated on new adsorbent materials better than silica gel. The named HKUST-1 (Cu-BTC (copper benzene-1,3,5-tricarboxylate), $C_{18}H_6Cu_3O_{12}$) with metal organic frameworks was new micro-porous material with an increase of water uptake of 93.2% compared to silica gel RD-2060 [101]. For an AlPO-18 (aluminophosphate) material [102], the highest water uptake was 0.253 g/g for the driving temperature of 95 °C, which was more than six times higher compared to the reference silica gel. However, those new materials still need further study for their practical utilization in low grade heat source powered water-evaporating adsorption cooling systems, but this is beyond the scope of this paper, so there is no further information to be given.

Modern research methods are necessary to detect the water adsorption in silica gel or adsorber. NMR microimaging technique was used to study water adsorption on a $CaCl_2$/silica single pellet [12]. And Asano et al. [103] applied a neutron radiography method to measure the hygroscopic water distribution in an adsorber. The transient characteristics of the hygroscopic water distributions in the granule bed were clearly visualized from the processed radiographs obtained by neutron radiography method. Those visual methods are important to improve the heat and mass transfer performance in the silica gel and the adsorber and then optimize the design of an adsorption heat exchanger because the resistance of the heat and mass transfer can be easily found through graphics.

At present, weak heat and mass transfer performance of adsorbent material has become the main bottleneck of the silica gel–water adsorption refrigeration technology and subsequently resulted in large size, low performance and high cost. In the future, the adsorption performance of silica gel should be further improved. Research about adsorption performance, composite adsorbent of silica gel and even new substitute for silica gel should be studied first. Afterwards, the improvement of adsorption cycles, adsorber configurations, theoretical and experimental methods, and system designs can be utilized in future commercial and industrial adsorption refrigeration systems.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under Contract no. 50806035. Authors would thank International Cooperation Program for Excellent Lectures of 2011 by Shandong Provincial Education Department, P.R. China.

References

[1] BP statistical review of world energy june. ⟨http://www.bp.com/⟩; 2012.
[2] Lior N. Sustainable energy development (May 2011) with some game-changers. Energy 2012;40(1):3–18.
[3] Mesut A, Murat E, Amir R, Shihab A. Model predictive HVAC load control in buildings using real-time electricity pricing. Energy and Buildings 2013;60:199–209.
[4] Yasuki H, Yukiteru S, Mitsuhiro K, Fujio W, Noriyuki K, Masanobu H, et al. Development of a suction-pump-assisted thermal and electrical hybrid adsorption heat pump. Applied Thermal Engineering 2008;28(13):1687–93.
[5] Dieng AO, Wang RZ. Literature review on solar adsorption technologies for ice-making and air-conditioning purposes and recent developments in solar technology. Renewable and Sustainable Energy Reviews 2001;5(4):313–42.
[6] Wang RZ, Oliveira RG. Adsorption refrigeration—an efficient way to make good use of waste heat and solar energy. Progress in Energy and Combustion Science 2006;32(4):424–58.
[7] Wang RZ, Ge TS, Chen CJ, Ma Q, Xiong ZQ. Solar sorption cooling systems for residential applications: options and guidelines. International Journal of Refrigeration 2009;32(4):638–60.
[8] Wang DC, Li YH, Li D, Xia YZ, Zhang JP. A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption systems. Renewable and Sustainable Energy Reviews 2010;14(1):344–53.
[9] Gupta Y, Metchop L, Frantzis A, Phelan PE. Comparative analysis of thermally activated, environmentally friendly cooling systems. Energy Conversion and Management 2008;49(5):1091–7.
[10] Wang DC, Zhang JP, Xia YZ, Han YP, Wang SW. Investigation of adsorption performance deterioration in silica gel–water adsorption refrigeration. Energy Conversion and Management 2012;58:157–62.
[11] Freni A, Sapienza A, Glaznev I S, Aristov YI, Giovanni R. Experimental testing of a lab-scale adsorption chiller using a novel selective water sorbent silica modified by calcium nitrate. International Journal of Refrigeration 2012;35(3):518–24.
[12] Koptyug IV, Khitrina LYu, Aristov YuI, Tokarev MM, Iskakov KT, Parmon VN, et al. An 1H NMR microimaging study of water vapor sorption by individual porous pellets. Journal of Physical Chemistry B 2000;104:1695–700.
[13] Restuccia G, Freni A, Vasta S, Aristov Yu. Selective water sorbent for solid sorption chiller: experimental results and modelling. International Journal of Refrigeration 2004;27(3):284–93.
[14] Daou K, Wang RZ, Yang GZ, Xia ZZ. Theoretical comparison of the refrigerating performances of a $CaCl_2$ impregnated composite adsorbent to those of the host silica gel. International Journal of Thermal Sciences 2008;47(1):68–75.
[15] Saha BB, Chakraborty A, Koyama S, Aristov YI. A new generation cooling device employing CaCl2-in-silica gel–water system. International Journal of Heat and Mass Transfer 2009;52(1–2):516–24.
[16] San JY, Hsu HC. Performance of a multi-bed adsorption heat pump using SWS-1L composite adsorbent and water as the working pair. Applied Thermal Engineering 2009;29(8–9):1606–13.
[17] Farid BC, Farid C, Francisco CM, Agustín FPC, Carlos MC. Water sorption on silica- and zeolite-supported hygroscopic salts for cooling system applications. Energy Conversion and Management 2012;53(1):219–23.
[18] Gong LX, Wang RZ, Xia ZZ, Chen CJ. Design and performance prediction of a new generation adsorption chiller using composite adsorbent. Energy Conversion and Management 2011;52(6):2345–50.
[19] Ng KC, Chua HT, Chung CY, Loke CH, Kashiwagi T, Akisawa A, et al. Experimental investigation of the silica gel–water adsorption isotherm characteristics. Applied Thermal Engineering 2001;21(16):1631–42.
[20] Henninger SK, Munz G, Ratzsch KF, Schossig P. Cycle stability of sorption materials and composites for the use in heat pumps and cooling machines. Renewable Energy 2011;36(11):3043–9.
[21] Aristov YI, Glaznev IS, Girnik IS. Optimization of adsorption dynamics in adsorptive chillers: loose grains configuration. Energy 2012;46(1):484–92.
[22] Eun TH, Song HK, Han JH, Lee KH, Kim JN. Enhancement of heat and mass transfer in silica-expanded graphite composite blocks for adsorption heat pumps: Part I. Characterization of the composite blocks. International Journal of Refrigeration 2000;23(1):64–73.
[23] Eun TH, Song HK, Han JH, Lee KH, Kim JN. Enhancement of heat and mass transfer in silica-expanded graphite composite blocks for adsorption heat pumps. Part II. Cooling system using the composite blocks. International Journal of Refrigeration 2000;23(1):74–81.
[24] Tso CY, Chao CYH. Activated carbon, silica-gel and calcium chloride composite adsorbents for energy efficient solar adsorption cooling and dehumidification systems. International Journal of Refrigeration 2012;35(6):1626–38.
[25] Solmuş İ, Rees DAS, Yamalı C, Baker D, Kaftanoğlu B. Numerical investigation of coupled heat and mass transfer inside the adsorbent bed of an adsorption cooling unit. International Journal of Refrigeration 2012;35(3):652–62.
[26] Freni A, Russo F, Vasta S, Tokarev M, YuI Aristov, Restuccia G. An advanced solid sorption chiller using SWS-1L. Applied Thermal Engineering 2007;27(13):2200–4.
[27] Ahamat MA, Tierney MJ. Calorimetric assessment of adsorbents bonded to metal surfaces: application to type A silica gel bonded to aluminium. Applied Thermal Engineering 2012;40:258–66.
[28] Rezk A, Al-Dadah RK, Mahmoud S, Elsayed A. Effects of contact resistance and metal additives in finned-tube adsorbent beds on the performance of silica gel/water adsorption chiller. Applied Thermal Engineering 2013;53(2):278–84.
[29] Li J, Kubota M, Watanabe F, Kobayashi N, Hasatani M. Optimal design of a fin-type silica gel tube module in the silica gel/water adsorption heat pump. Journal of Chemical Engineering of Japan 2004;37(4):551–7.
[30] Mitsuhiro K, Takeshi U, Ryo F, Jun K, Fujio W, Noriyuki K, et al. Cooling output performance of a prototype adsorption heat pump with fin-type silica gel tube module. Applied Thermal Engineering 2008;28(2–3):87–93.
[31] Hamid N, Hoda T, Mehdi M. Bed geometrical specification effects on the performance of silica/water adsorption chillers. International Journal of Refrigeration 2012;35(8):2261–74.
[32] Khan MZI, Alam KCA, Saha BB, Akisawa A, Kashiwagi T. Study on a re-heat two-stage adsorption chiller – the influence of thermal capacitance ratio, overall thermal conductance ratio and adsorbent mass on system performance. Applied Thermal Engineering 2007;27(10):1677–85.

[33] Miyazaki T, Akisawa A. The influence of heat exchanger parameters on the optimum cycle time of adsorption chillers. Applied Thermal Engineering 2009;29(13):2708–17.
[34] Alam KCA, Saha BB, Kang YT, Akisawa A, Kashiwagi T. Heat exchanger design effect on the system performance of silica gel adsorption refrigeration systems. International Journal of Heat and Mass Transfer 2000;43(24):4419–31.
[35] Farid SK, Billah MM, Khan MZI, Rahman MM, Shari UM. A numerical analysis of cooling water temperature of two-stage adsorption chiller along with different mass ratios. International Communications in Heat and Mass Transfer 2011;38(8):1086–92.
[36] Hamamoto Y, Alam AKC, Akisawa A, Kashiwagi T. Performance evaluation of a two-stage adsorption refrigeration cycle with different mass ratio. International Journal of Refrigeration 2005;28(3):344–52.
[37] Cho SH, Kim JN. Modeling of a silica gel/water adsorption-cooling system. Energy 1992;17(9):829–39.
[38] Saha BB, Boelman EC, Kashiwagi T. Computer simulation of a silica gel–water adsorption refrigeration cycle—the influence of operating conditions on cooling output and COP. ASHRAE Transactions 1995;101(Pt 2):348–57.
[39] Boelman EC, Saha BB, Kashiwagi T. Experimental investigation of a silica gel–water adsorption refrigeration cycle—the influence of operating conditions on cooling output and COP. ASHRAE Transactions 1995;101(Pt 2):358–66.
[40] Wang XL, Chua HT, Ng KC. Experimental investigation of silica gel–water adsorption chillers with and without a passive heat recovery scheme. International Journal of Refrigeration 2005;28(5):756–65.
[41] Wang XL, Chua HT. A comparative evaluation of two different heat-recovery schemes as applied to a two-bed adsorption chiller. International Journal of Heat and Mass Transfer 2007;50(3–4):433–43.
[42] Akahira A, Alam KCA, Hamamoto Y, Akisawa A, Kashiwagi T. Mass recovery adsorption refrigeration cycle—improving cooling capacity. International Journal of Refrigeration 2004;27(3):225–34.
[43] Akahira A, Alam KCA, Hamamoto Y, Akisawa A, Kashiwagi T. Experimental investigation of mass recovery adsorption refrigeration cycle. International Journal of Refrigeration 2005;28(4):565–72.
[44] Akahira A, Alam KCA, Hamamoto Y, Akisawa A, Kashiwagi T. Mass recovery four-bed adsorption refrigeration cycle with energy cascading. Applied Thermal Engineering 2005;25(11–12):1764–78.
[45] Uyun AS, Akisawa A, Miyazaki T, Ueda Y, Kashiwagi T. Numerical analysis of an advanced three-bed mass recovery adsorption refrigeration cycle. Applied Thermal Engineering 2009;29(14–15):2876–84.
[46] Liu Y, Leong KC. Numerical study of a novel cascading adsorption cycle. International Journal of Refrigeration 2006;29(2):250–9.
[47] Saha BB, Boelman EC, Kashiwagi T. Computational analysis of an advanced adsorption–refrigeration cycle. Energy 1995;20(10):983–94.
[48] Saha BB, Akisawa A, Kashiwagi T. Silica gel water advanced adsorption refrigeration cycle. Energy 1997;22(4):437–47.
[49] Khan MZI, Alam KCA, Saha BB, Akisawa A, Kashiwagi T. Performance evaluation of multi-stage, multi-bed adsorption chiller employing re-heat scheme. Renewable Energy 2008;33(1):88–98.
[50] Alam AA, Hamamoto Y, Akisawa A, Kashiwagi T, Saha BB, Koyama S, et al. Multi-bed multi-stage adsorption refrigeration cycle-reducing driving heat source temperature. Transactions of Japan Society of Refrigeration and Air Conditioning Engineers 2003;20(3):413–20.
[51] Saha BB, Koyama S, Kashiwagi T, Akisawa A, Ng KC, Chua HT. Waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system. International Journal of Refrigeration 2003;26(7):749–57.
[52] Saha BB, Koyama S, Ng KC, Hamamoto Y, Akisawa A, Kashiwagi T. Study on a dual-mode, multi-stage, multi-bed regenerative adsorption chiller. Renewable Energy 2006;31(13):2076–90.
[53] Saha BB, Koyama S, Lee JB, Kuwahara K, Alam KCA, Hamamoto Y, et al. Performance evaluation of a low-temperature waste heat driven multi-bed adsorption chiller. International Journal of Multiphase Flow 2003;29(8):1249–63.
[54] Chua HT, Ng KC, Malek A, Kashiwagi T, Akisawa A, Saha BB. Multi-bed regenerative adsorption chiller—improving the utilization of waste heat and reducing the chilled water outlet temperature fluctuation. International Journal of Refrigeration 2001;24(2):124–36.
[55] Miyazaki T, Akisawa A, Saha BB, El-Sharkawy II, Chakraborty A. A new cycle time allocation for enhancing the performance of two-bed adsorption chillers. International Journal of Refrigeration 2009;32(5):846–53.
[56] Saha BB, Boelman EC, Kashiwagi T. Computer simulation of a silica gel–water adsorption refrigeration cycle–the influence of operating conditions on cooling output and COP. ASHRAE Transactions Research 1995;101(2):348–57.
[57] Boelman EC, Saha BB, Kashiwagi T. Parametric study of a silica gel–water adsorption refrigeration cycle—the influence of thermal capacitance and heat exchanger UA-values on cooling capacity, power density and COP. ASHRAE Transactions 1997;103(1):139–48.
[58] Chua HT, Ng KC, Malek A, Kashiwagi T, Akisawa A, Saha BB. Modeling the performance of two-bed, silica gel–water adsorption chillers. International Journal of Refrigeration 1999;22(3):194–204.
[59] Chua HT, Ng KC, Wang W, Yap C, Wang XL. Transient modeling of a two-bed silica gel–water adsorption chiller. International Journal of Heat and Mass Transfer 2004;47(4):659–69.
[60] Wang XL, Chua HT. Two bed silica gel–water adsorption chillers: an effectual lumped parameter model. International Journal of Refrigeration 2007;30(8):1417–26.
[61] Ibrahim IES. On the linear driving force approximation for adsorption cooling applications. International Journal of Refrigeration 2011;34(3):667–73.
[62] Alam KCA, Kang YT, Saha BB, Akisawa A, Kashiwagi T. A novel approach to determine optimum switching frequency of a conventional adsorption chiller. Energy 2003;28(10):1021–37.
[63] Saha BB, El-Sharkawy II, Chakraborty A, Koyama S, Banker ND, Dutta P, et al. Evaluation of minimum desorption temperatures of thermal compressors in adsorption refrigeration cycles. International Journal of Refrigeration 2006;29(7):1175–81.
[64] Voyiatzis E, Palyvos JA, Markatos NC. Heat-exchanger design and switching-frequency effects on the performance of a continuous type solar adsorption chiller. Applied Energy 2008;85(12):1237–50.
[65] Ahmed RMR, Raya KAD. Physical and operating conditions effects on silica gel/water adsorption chiller performance. Applied Energy 2012;89(1):142–9.
[66] Hamid N, Hoda T, Mehdi M. Bed geometrical specification effects on the performance of silica/water adsorption chillers. International Journal of Refrigeration 2012;35(8):2261–74.
[67] Hamid N, Iman D. Numerical simulation of heat and mass transfer in adsorbent beds with annular fins. International Journal of Refrigeration 2012;35(3):581–93.
[68] Freni A, Maggio G, Cipitì F, Aristov YI. Simulation of water sorption dynamics in adsorption chillers: one, two and four layers of loose silica grains. Applied Thermal Engineering 2012;44:69–77.
[69] Santori G, Sapienza A, Freni A. A dynamic multi-level model for adsorptive solar cooling. Renewable Energy 2012;43:301–12.
[70] Solmuş İ, Rees DAS, Yamalı C, Baker D. A two-energy equation model for dynamic heat and mass transfer in an adsorbent bed using silica gel/water pair. International Journal of Heat and Mass Transfer 2012;55(19–20):5275–88.
[71] Solmuş İ, Rees DAS, Yamalı C, Baker D, Bilgin K. Numerical investigation of coupled heat and mass transfer inside the adsorbent bed of an adsorption cooling unit. International Journal of Refrigeration 2012;35(3):652–62.
[72] Chang WS, Wang CC, Shieh CC. Experimental study of a solid adsorption cooling system using flat-tube heat exchangers as adsorption bed. Applied Thermal Engineering 2007;27(13):2195–9.
[73] 〈http://www.greenchiller.biz/〉.
[74] Liu YL, Wang RZ, Xia ZZ. Experimental study on a continuous adsorption water chiller with novel design. International Journal of Refrigeration 2005;28(2):218–30.
[75] Tomas N, Walter M, Hans-Martin H. Development of an adsorption chiller and heat pump for domestic heating and air-conditioning applications. Applied Thermal Engineering 2007;27(13):2205–12.
[76] Wang DC, Xia ZZ, Wu JY, Wang RZ, Zhai H, Dou WD. Study of a novel silica gel–water adsorption chiller. Part I. Design and performance prediction. International Journal of Refrigeration 2005;28(7):1073–83.
[77] Wang DC, Wu JY, Xia ZZ, Zhai H, Wang RZ, Dou WD. Study of a novel silica gel–water adsorption chiller. Part II. Experimental study. International Journal of Refrigeration 2005;28(7):1084–91.
[78] Wang DC, Shi ZX, Yang QR, Tian XL, Zhang JC, Wu JY. Experimental research on novel adsorption chiller driven by low grade heat source. Energy Conversion and Management 2007;48(8):2375–81.
[79] Lu ZS, Wang RZ, Xia ZZ. Experimental analysis of one adsorption air conditioning with micro-porous silica gel–water. Applied Thermal Engineering 2013;50(1):1015–20.
[80] Yang GZ, Xia ZZ, Wang RZ, Keletigui D, Wang DC, Dong ZH, et al. Research on a compact adsorption room air conditioner. Energy Conversion and Management 2006;47(15–16):2167–77.
[81] Chen CJ, Wang RZ, Xia ZZ, Kiplagat JK. Study on a silica gel–water adsorption chiller integrated with a closed wet cooling tower. International Journal of Thermal Sciences 2010;49(3):611–20.
[82] Chen CJ, Wang RZ, Xia ZZ, Kiplagat JK, Lu ZS. Study on a compact silica gel–water adsorption chiller without vacuum valves: design and experimental study. Applied Energy 2010;87(8):2673–81.
[83] Lu ZS, Wang RZ, Xia ZZ, Wu QB, Sun YM, Chen ZY. An analysis of the performance of a novel solar silica gel–water adsorption air conditioning. Applied Thermal Engineering 2011;31(17–18):3636–42.
[84] Saha BB, Akisawa A, Kashiwagi T. Solar/waste heat driven two-stage adsorption chiller: the prototype. Renewable Energy 2001;23(1):93–101.
[85] Di J, Wu JY, Xia ZZ, Wang RZ. Theoretical and experimental study on characteristics of a novel silica gel–water chiller under the conditions of variable heat source temperature. International Journal of Refrigeration 2007;30(3):515–26.
[86] Wang DC, Wang YJ, Zhang JP, Tian XL, Wu JY. Experimental study of adsorption chiller driven by variable heat source. Energy Conversion and Management 2008;49(5):1063–73.
[87] Wu JY, Li S. Study on cyclic characteristics of silica gel–water adsorption cooling system driven by variable heat source. Energy 2009;34(11):1955–62.
[88] Zhang G, Wang DC, Zhang JP, Han YP, Wanchao Sun. Simulation of operating characteristics of the silica gel–water adsorption chiller powered by solar energy. Solar Energy 2011;85(7):1469–78.
[89] Tangkengsirisin V, Kanzawa A, Watanabe T. A solar-powered adsorption cooling system using a silica gel–water mixture. Energy 1998;23(5):347–53.

[90] Luo HL, Wang RZ, Dai YJ, Wu JY, Shen JM, Zhang BB. An efficient solar-powered adsorption chiller and its application in low-temperature grain storage. Solar Energy 2007;81(5):607–13.
[91] Luo HL, Dai YJ, Wang RZ, Wu JY, Xu YX, Shen JM. Experimental investigation of a solar adsorption chiller used for grain depot cooling. Applied Thermal Engineering 2006;26(11–12):1218–25.
[92] Zhai XQ, Wang RZ, Wu JY, Dai YJ, Ma Q. Design and performance of a solar-powered air-conditioning system in a green building. Applied Energy 2008;85(5):297–311.
[93] Zhai H, Dai YJ, Wu JY, Wang RZ. Energy and exergy analyses on a novel hybrid solar heating, cooling and power generation system for remote areas. Applied Energy 2009;86(9):1395–404.
[94] Lu ZS, Wang RZ, Xia ZZ, Lu XR, Yang CB, Ma YC, et al. Study of a novel solar adsorption cooling system and a solar absorption cooling system with new CPC collectors. Renewable Energy 2013;50:299–306.
[95] Chang WS, Wang CC, Shieh CC. Design and performance of a solar-powered heating and cooling system using silica gel/water adsorption chiller. Applied Thermal Engineering 2009;29(10):2100–5.
[96] Kong XQ, Wang RZ, Wu JY, Huang XH, Huangfu Y, Wu DW, et al. Experimental investigation of a micro-combined cooling, heating and power system driven by a gas engine. International Journal of Refrigeration 2005;28(7):977–87.
[97] Li S, Wu JY. Theoretical research of a silica gel–water adsorption chiller in a micro combined cooling, heating and power (CCHP) system. Applied Energy 2009;86(6):958–67.
[98] Ruud JHG, Simon FS, Robert DB. Waste heat driven silica gel/water adsorption cooling in trigeneration. Applied Thermal Engineering 2010;30(8–9):1039–46.
[99] Derek KB. Thermodynamic limits to thermal regeneration in adsorption cooling cycles. International Journal of Refrigeration 2008;31(1):55–64.
[100] San JY, Lin WM. Comparison among three adsorption pairs for using as the working substances in a multi-bed adsorption heat pump. Applied Thermal Engineering 2008;28(8–9):988–97.
[101] Rezk A, Al-Dadah R, Mahmoud S, Elsayed A. Characterisation of metal organic frameworks for adsorption cooling. International Journal of Heat and Mass Transfer 2012;55(25–26):7366–74.
[102] Henninger SK, Schmidt FP, Henning HM. Water adsorption characteristics of novel materials for heat transformation applications. Applied Thermal Engineering 2010;30(13):1692–702.
[103] Asano H, Nakajima T, Takenaka N, Fujii T. Visualization of the hygroscopic water distribution in an adsorbent bed by neutron radiography. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2005;542(1–3):241–7.